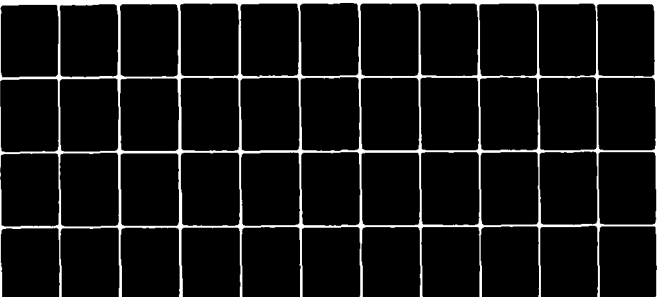
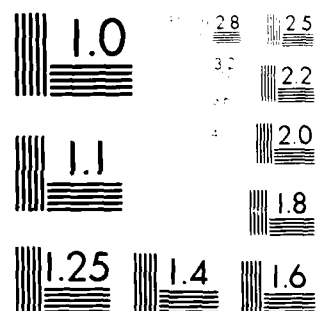


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AGARDograph No. 265
A COMPILATION OF UNSTEADY TURBULENT BOUNDARY LAYER
EXPERIMENTAL DATA

by

Lawrence W. Carr

U.S. Army Aeromechanics Laboratory
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California - U.S.A.



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A COMPILATION OF UNSTEADY TURBULENT BOUNDARY-LAYER EXPERIMENTAL DATA

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SUMMARY

A comprehensive literature search was conducted and those experiments related to unsteady turbulent boundary-layer behavior were cataloged. In addition, an international survey of industrial, university, and governmental research laboratories was made, in which new and ongoing experimental programs associated with unsteady turbulent boundary-layer research were identified. Pertinent references were reviewed and classified based on the technical emphasis of the various experiments. Experiments that include instantaneous or ensemble-averaged profiles of boundary-layer variables are stressed. Detailed reviews that include descriptions of the experimental apparatus, flow conditions, summaries of acquired data, and significant conclusions are made. The measurements made in these experiments that exist in digital form have been stored on magnetic tape, and instructions are presented for accessing these data sets for further analysis.

SYMBOLS

A	amplitude of periodic quantity	u_e	instantaneous longitudinal velocity at edge of boundary layer
A_f	flap amplitude	u_p	periodic component of longitudinal velocity
a_∞	speed of sound in free stream	u^*	friction velocity
C	traveling wave velocity	u'	random longitudinal velocity fluctuation
C_f	skin friction coefficient	u^+	nondimensional velocity in wall coordinates
C_p	pressure coefficient	$u'v'$	instantaneous turbulent Reynolds stress
c	chord	v	instantaneous vertical velocity in boundary layer
D	diameter	v'	random vertical velocity fluctuation
f	frequency, Hz	x, X	longitudinal distance
f_t	characteristic frequency of turbulence	x_0	reference station, also location at which measurements were made
H	shape factor	y	vertical distance
i	mean incidence of airfoil	y^+	vertical distance in wall coordinates ($y^+ = yu^*/\nu$)
L	length of diffuser	z	spanwise distance
M_∞	free-stream Mach number	α	angle of attack; also amplitude parameter
p	static pressure	δ	boundary-layer thickness
q	dynamic pressure	δ^*	displacement thickness
r	rms value of turbulence intensity; also radial distance	ϵ	eddy viscosity
R	radius of pipe	η	nondimensional vertical coordinate ($\eta = y/\delta$)
Re_x	Reynolds number based on x	θ	momentum thickness
Re_c	Reynolds number based on chord	ν	kinematic viscosity
Re_θ	Reynolds number based on θ	ρ	density
R_{11}	u'^2 component of Reynolds stress tensor	τ	shear stress
R_{12}	$u'v'$ component of Reynolds stress tensor	ϕ	phase angle
R_{22}	v'^2 component of Reynolds stress tensor	ϕ_0	phase position in cycle for ensemble average
S	Strouhal number	ω	rotational frequency, rad/sec
T	period of one cycle, sec	<u>Subscripts and Annotations</u>	
TKE	turbulent kinetic energy function	() _p	periodic component
t	time, sec	() _e	at edge of boundary layer
U_0	time-averaged mean of longitudinal velocity at edge of boundary layer	() _{rms}	rms value
U_1	amplitude of imposed oscillation at edge of boundary layer (% of U_0)	()	ensemble average
U_∞	free-stream velocity in steady flow at reference location	()	mean value
u	instantaneous longitudinal velocity in boundary layer	() _{p1}	first harmonic of periodic component
u_A	velocity signal from wire A of x-wire probe	$\Delta()$	difference in parameter
u_B	velocity signal from wire B of x-wire probe	() _w	measured at wall
u_{CL}	longitudinal velocity at centerline of diffuser	() _{CL}	measured at centerline
		() ₀	at specified measurement station

INTRODUCTION

Unsteady turbulent boundary layers play an important role in the performance of many fluid-dynamic systems; e.g., helicopter rotor blades, jet engine compressors, heat exchangers, and transonic airfoil behavior all depend on unsteady turbulent boundary-layer characteristics. The need for better techniques of predicting performance has been acute, and many theoretical methods have been proposed in the last decade. Unfortunately, the experimental data needed to properly assess these methods have not been readily available. For example, one experimental study of the unsteady turbulent boundary layer on a flat plate has been frequently cited (Karlsson, 1959); however, the results of that experiment have been available only in graphic form, with the result that significant errors can be made when interpreting the data. Data from several other experiments that have been conducted are not readily accessible; indeed the existence of many of these experiments is not widely known. Moreover, new experiments are in progress and still others are being proposed.

An international survey of industrial, university, and governmental laboratories was conducted to identify both new and ongoing programs associated with unsteady turbulent boundary-layer research, as well as to identify experiments that have already been published. In order to put these experiments in perspective, and to publicize the existence of many of these works, the present compilation was undertaken.

This report has two goals: (1) to provide a complete catalog of existing experimental research performed on unsteady turbulent boundary-layer behavior, and (2) to compile all existing experimental data in a single source, so that future research in this area can be based on a clearly defined and fully documented data base.

SCOPE

It is intended that this report provide a comprehensive data library of unsteady turbulent boundary-layer experiments containing information on all experiments of this type. Experimental research in unsteady turbulent boundary-layer behavior is a very complex and difficult task. Recent technical advances in flow measurement techniques and computer technology have permitted more detailed measurements of flow parameters than ever before, and several new experiments are in progress. However, many exploratory experiments have been performed in the past that can provide guidance and insight into the characteristics of unsteady turbulent boundary-layer behavior. The range of variables in many of these experiments is quite limited; each experiment required specialized equipment, and there is little overlap between test results. Moreover, the tests vary greatly in sophistication and detail.

All the surveyed experiments that contain instantaneous measurements of unsteady turbulent boundary-layer parameters have been included in this report, so that a complete data bank can be established. It is expected that this will allow further analysis of these experiments and offer an opportunity for application of modern analytical techniques to these data. Whenever possible, original digital data supplied by the various principal investigators has been used for the data base, so that as much as possible of the information contained in these experiments could be made available for use. No independent review of the data has been performed at this time. Emphasis has been on flows in contact with physical boundaries; for this reason, unsteady jet and wake studies have not been included. Unsteady transition was considered beyond the scope of this work; however, since the effects of unsteady transition often affect the resultant turbulent boundary layer, a bibliography of transition experiments is included in the list of references.

COMPILATION OF EXPERIMENTAL DATA

Selection Procedure

The survey of the literature uncovered a wide variety of pertinent reports. Since the technical emphasis of these experiments is so diverse, it has been necessary to classify the various reports according to the primary objectives of the associated research. Experiments presenting instantaneous or ensemble-averaged profiles have been selected for special documentation, and a detailed description of the experimental facility, a listing of the available results, and a summary of the important conclusions have been prepared for each of them. These descriptive summaries are presented alphabetically by principal author; Table 1 shows the format that has been used. Where digital data are available, details of the magnetic tape digital file are included; these experiments are identified as Class A flows. Because of a variety of causes, digital data are not available for many important experiments. In some cases, the digital data no longer exist; for others, the data do exist but were not available at the time of this publication. These experiments have been documented using the same format as that used for the Class A flows outlined above, but they are identified as Class B flows. In addition, there are several other experiments that contain useful information about unsteady turbulent boundary-layer flow behavior. However, in some only time-averaged data analysis was performed; others were performed at very low amplitude, or do not contain sufficient data to be included in the primary data bank. These experiments have been identified as Class C, and are cited without details; the interested reader is referred to the original documents for further information.

These three classes of experiments are presented in Tables 2 and 3. Flow Classes A and B are indicated by bold type, and details of these flows can be found under the corresponding flow name in the catalog of detailed experiments. The experiments with digital data on file (Class A) are marked by an asterisk adjacent to the flow title. Class C flows are indicated by light type, and are specified by the appropriate reference.

Presentation of the actual digital data for Class A experiments has been restricted to the digital tapes since in many cases the data sets are of very large magnitude. To include the maximum amount of digital data within the time constraints imposed by the publication schedule, many of the data sets are presented in the format supplied by the original authors. In each case, a computer program is included on the digital tape which permits ready access to the corresponding data set.

Table 1 Standard format for review of experiments

<u>EXPERIMENT</u>	<u>DATA</u>
FLOW TITLE	MEASUREMENT TECHNIQUE
FLOW TYPE	DATA REDUCTION TECHNIQUE
PARTICIPATING RESEARCH PERSONNEL	NOMINAL TEST CONDITIONS
PRIMARY REFERENCE	AVAILABILITY OF DATA
FACILITY	GRAPHIC DATA PRESENTED IN REPORT(S)
LOCATION	DATA ON MAGNETIC TAPE
APPARATUS	COMMENTS BY AUTHORS
TEST SECTION	COMMENTS BY LAWRENCE W. CARR (LWC)
OSCILLATION MECHANISM	RELATED REFERENCES
PRESSURE GRADIENT MECHANISM	
MEASUREMENT SURFACE	
TRIP	
WALL BOUNDARY-LAYER CONTROL	
NATURAL FREQUENCY	
MAXIMUM WALL DEFLECTION	
POSITIONAL ACCURACY	
FREE-STREAM TURBULENCE	
VERIFICATION OF TWO-DIMENSIONALITY	
MEASUREMENT ACCURACY	

Table 2 Existing unsteady turbulent boundary-layer experiments. Bold type indicates experiments that are reviewed in detail. Asterisk (*) indicates that digital data are available on magnetic tape

<u>dp/dx = 0</u>	<u>dp/dx > 0</u>	<u>SEPARATION</u>
ACHARYA*	BREMBATI	BANNER & MELVILLE
BINDER	COUSTEIX III*	COUSTEIX III*
COUSTEIX I*	FORESMAN	KENISON
COUSTEIX II*	KENISON	SIMPSON*
CHARNAY & MELINAND	OSTROWSKI	
HUSSAIN & REYNOLDS	PARIKH*	
JACOBS	PERICLEOUS	
JONNISON*	PITTALUGA	
KARLSSON*	RAKOWSKY	
KENDALL	SCHACHENMANN	
MILLER	SIMPSON*	
MORRISSEY	STENNING & SCHACHENMANN	
NORRIS & REYNOLDS	THOMAS & SHUKLA	
PATEL*	TOMSHO*	
RONNEBERGER & AHRENS		

DATA ANALYSIS TECHNIQUES

A variety of analog and digital techniques have been used for determining the characteristics of unsteady turbulent boundary layers. For example, the instantaneous velocity has been measured in many different ways: electrochemically (Mizushima et al., 1973); by use of a micropropeller (Jonsson and Carlsen, 1976); with hot-wire anemometers (Cousteix et al., 1977); with single-beam lasers (Parikh et al., 1981b); and with dual-beam lasers (Simpson et al., 1980). As seen in Fig. 1, many levels of sophistication can be employed for analysis of the resultant signal; four that have been used in existing experimental studies are listed below.

Level I: Time-Averaged Mean

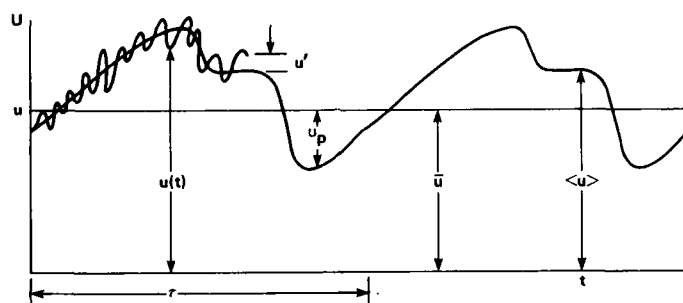
The time-averaged mean value of the experimental signal is the least difficult to determine; it can be obtained by performing a digital or analog long-time average of the fluctuating signal. However, as explained in Carr (1981), the result of a time-averaging process should be viewed with caution because many different types of unsteady flows can produce time-averaged mean values that are identical.

Level II: Periodic Component

The next level of sophistication in data analysis is the extraction of the periodic component of the fluctuating signal. One technique which is often used is the cross-correlation of the experimentally obtained fluctuating signal with a once-per-cycle trigger, or with a sine-wave signal generated by the drive mechanism

Table 3 Additional unsteady viscous flow experiments. Bold type indicates experiments that are reviewed in detail. Asterisk () * indicates that digital data are available on magnetic tape

PIPE	AIRFOILS AND CASCADES	NEW EXPERIMENTS
BROWN et al.	CARR, McALISTER & McCROSKEY	COUSTEIX et al. (1981)
GERRARD	EVANS	DE RUYCK & HIRSCH
KITA et al.	GOSTELOW	EHRENSBERGER
LU	HO & CHEN	KOBASHI & HAYAKAWA
MAINARDI & PANDAY	MARVIN*	LORBER & COVERT
MIZUSHINA I	SAXENA	RAMAPRIAN & TU (1981)
MIZUSHINA II		REYNOLDS et al.
OHMI		RICHTER & RONNEBERGER
RAMAPRIAN*		SIMPSON et al. (1991)
SCHULTZ GRUNOW		WEINSTEIN



$u(t)$ - INSTANTANEOUS MEASURED VELOCITY	$u(t) = \bar{u} + u_p + u'$
\bar{u} - TIME AVERAGED MEAN VELOCITY	$\bar{u} = \frac{1}{T} \int_0^T u(t) dt$
$\langle u \rangle$ - ENSEMBLE AVERAGED VELOCITY	$\langle u(t) \rangle = \frac{1}{N} \sum_{n=0}^N u(t + n\tau)$
u_p - PERIODIC COMPONENT OF VELOCITY	$u_p(t) = \langle u(t) \rangle - \bar{u}$
u' - RANDOM FLUCTUATIONS OF VELOCITY	$u'(t) = u(t) - \langle u(t) \rangle$

Figure 1 Analysis of unsteady turbulent velocity signal

of an oscillating flow facility. This results in amplitude and phase data for the first harmonic content of the fluctuating signal compared with the reference signal. This approach is satisfactory for many small amplitude oscillations, and has been used by several investigators. However, any higher harmonic content of the original signal becomes indistinguishable from the random fluctuations caused by turbulence; this limits the accuracy of this method, regardless of the amplitude of the oscillation.

Level III: Ensemble Average

The ensemble-average approach is based on the assumption that the physical phenomenon under study is repeatable (not necessarily periodic). If the initiation of the event under study can be recognized (a once-per-cycle pulse, for example), then a sequence of samples of the signal to be studied can be obtained at discrete intervals of time. Repetition of this process of sampling results in many sets of discrete samples of the experimental signal. In turbulent flow, this signal is composed of a mean velocity magnitude, \bar{u} , a deterministic signal which is repeated each time the event takes place, u_p , and random fluctuations u' that are uncorrelated with the organized flow, as follows:

$$u = \bar{u} + u_p + u'$$

Based on the ensemble sampling procedure outlined above, the various components of the full experimental signal u can be obtained. During each event that is digitized, N samples (u_n), each Δt apart, are recorded; thus the mean value will be

$$\bar{u} = \frac{1}{N} \sum_{n=1}^N u_n$$

If the event is digitized for M recurrences, and the results are summed at each of the N sample points, the ensemble average of the signal at the N sample points will result:

$$\langle u \rangle_n = \frac{1}{M} \sum_{m=1}^M u_{m,n}$$

The full ensemble average of the signal, $\langle u \rangle$, is thus the set

$$\left\{ \frac{1}{M} \sum_{m=1}^M u_{m,n} \right\}_{n=1,N}$$

The deterministic part of the signal thus becomes

$$u_p = \langle u \rangle - \bar{u}$$

and the random fluctuation is

$$u' = u - \langle u \rangle$$

This method is useful for periodic signals such as those resulting from oscillatory drive experiments, as well as aperiodic experiments such as impulsively started experiments, when they are repeated many times. All the harmonics are retained in the signal u_p (within the sampling bandwidth). Typically, 100-200 samples are recorded per cycle, so that if unsteady velocity profiles are measured at several x stations, significant storage capability is required.

Level IV: Multiple Component Ensemble Average

The highest level of data analysis that has been used for presently published unsteady turbulent boundary-layer experiments is the multiple-component ensemble average. This procedure requires simultaneous measurement of two instantaneous signals; the resultant values are then combined to form a single variable which is then ensemble averaged. A common example of this technique is the experimentally determined instantaneous Reynolds shear stress $\langle u'v' \rangle$.

A summary of all the existing experimental measurements that have been identified are presented in Tables 4 and 5. In these tables, bold type indicates data recorded by the originating author; light type denotes information that can be reconstructed from data presented in the supporting documents (e.g., Tomsho supplied ensemble-averaged data for velocity; the time-averaged mean velocity can then be reconstructed from this information).

Table 4 Summary of available unsteady turbulent boundary layer data - levels I and II (bold type indicates data that are available directly from reports; light type indicates data that can be reconstructed from the published data; asterisk ()* indicates experiments not reviewed herein but cited in reference list)

I		II
\bar{u}	\bar{u}^2	$u_p(A; \phi)$
ACHARYA	ACHARYA	ACHARYA
BREMBATI	COUSTEIX I	BINDER
COUSTEIX I	COUSTEIX II	COUSTEIX I
COUSTEIX II	COUSTEIX III	COUSTEIX II
COUSTEIX III	JACOBS*	COUSTEIX III
EVANS	KARLSSON	EVANS
JACOBS*	KENDALL	HUSSAIN & REYNOLDS
JONNISON	MIZUSHINA I	KARLSSON
KARLSSON	MIZUSHINA II	KENISON
KENDALL	PARIKH	JONNISON
KENISON	PATEL	KENDALL
LU	PERICLEOUS	LU
MILLER*	RAMAPRIAN	MIZUSHINA I
MIZUSHINA I	SCHACHENMANN	MIZUSHINA II
MIZUSHINA II	STENNING & SCHACHENMANN*	OHMI
OHMI		PATEL
PARIKH		PERICLEOUS
PATEL		RAMAPRIAN
RAMAPRIAN		SIMPSON
SCHACHENMANN		TOMSHO
SIMPSON		
STENNING & SCHACHENMANN*		
TOMSHO		

Table 5. Summary of available unsteady turbulent boundary layer data - levels III and IV (bold type indicates data that are available directly from reports; light type indicates data that can be reconstructed from the published data; asterisk ()* indicates experiments not detailed herein but cited in reference list)

III		IV
$\langle u \rangle$	$\langle u^2 \rangle$	$\langle u'v' \rangle$
BREMBATI	BREMBATI	COUSTEIX II
COUSTEIX I	COUSTEIX II	COUSTEIX III
COUSTEIX II	COUSTEIX III	KENDALL
COUSTEIX III	KENDALL	MIZUSHINA II
EVANS	MIZUSHINA I	RAMAPRIAN
GOSTELOW*	MIZUSHINA II	SIMPSON
JONNISON	RAMAPRIAN	
KENDALL	SIMPSON	
MIZUSHINA I		
MIZUSHINA II		
OHMI		
OSTROWSKI		
RAMAPRIAN		
SAXENA		
SIMPSON		
TOMSHO		

CATALOG OF SELECTED EXPERIMENTS

The data library contains detailed descriptions of Class A and Class B flows using the format presented in Table 1. The experiments are arranged alphabetically, and a list of the titles and flow descriptors follows:

ACHARYA	Class A, fixed flat surface, zero pressure gradient, channel flow
BINDER	Class B, fixed flat surface, zero pressure gradient, boundary layer
BREMBATI	Class B, fixed flat surface, nonzero pressure gradient, boundary layer
COUSTEIX (I)	Class A, fixed flat surface, zero pressure gradient, boundary layer
COUSTEIX (II)	Class A, fixed flat surface, zero pressure gradient, boundary layer
COUSTEIX (III)	Class A, fixed flat surface, adverse pressure gradient, boundary layer
EVANS	Class B, fixed airfoil surface, adverse pressure gradient, boundary layer
JOHNSON	Class A, fixed flat surface, zero pressure gradient, zero mean velocity, boundary layer
KARLSSON	Class A, fixed flat surface, zero pressure gradient, boundary layer
KENDALL	Class B, waving surface, zero pressure gradient, boundary layer
KENISON	Class B, fixed flat surface, adverse pressure gradient, time-dependent traveling wave, boundary layer
LU	Class B, fixed surface, fully developed pipe flow
MARVIN	Class A, fixed airfoil surface, adverse pressure gradient, shock-induced flow oscillation, boundary layer
MIZUSHINA (I)	Class B, fixed surface, fully developed pipe flow
MIZUSHINA (II)	Class B, fixed surface, fully developed pipe flow
OHMI	Class B, fixed surface, fully developed pipe flow
OSTROWSKI	Class B, fixed flat surface, boundary layer, impulsive start
PARIKH	Class A, fixed flat surface, adverse pressure gradient, boundary layer
PATEL	Class A, fixed flat surface, zero pressure gradient, time-dependent traveling wave, boundary layer
PERICLEOUS	Class A, fixed curved surface, time-dependent traveling wave plus mean adverse pressure gradient, boundary layer
RAMAPRIAN	Class A, fixed surface, fully developed pipe flow
SAXENA	Class B, fixed airfoil, adverse pressure gradient, boundary layer
SCHACHENMANN	Class B, fixed axisymmetric diffuser, adverse pressure gradient, boundary layer
SIMPSON	Class A, fixed flat surface, adverse pressure gradient, boundary layer
TOMSHO	Class B, fixed axisymmetric diffuser, adverse pressure gradient, boundary layer

Flow title: ACHARYA

Flow type: Class A, fixed flat surface, zero pressure gradient, channel flow

Participating research personnel: M. Acharya and W. C. Reynolds

Primary reference: Measurements and Predictions of a Fully Developed Turbulent Channel Flow with Imposed Controlled Oscillations. Acharya and Reynolds, 1975

Facility:

Location: Department of Mechanical Engineering, Stanford U., Stanford, Calif.

Apparatus: Two-dimensional air channel (see Fig. 2)

Test Section: 2.44 m long, 0.064 m wide, 1.14 m high; measurements made at end. Test section preceded by 12.19 m development section

Oscillation mechanism: Rotating, hollow vertical cylinder placed at end of test section, with three vertical slots placed around circumference having cross section equal to that of test section.

Amplitude controlled by bypassing predetermined amount of air past cylinder.

Pressure-gradient mechanism: None

Measurement surface: Back surface of test section (lined with 1/16-in. Formica panels, flat to ± 0.13 mm)

Trip: Not specified

Wall boundary-layer control: Not specified

Natural frequency: Theory and tests demonstrated that no natural frequency effects could appear in test section for frequencies studied

Maximum wall deflection: Less than 0.005 mm at all frequencies at data station

Positional accuracy: ± 0.05 mm

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: u : 0.067 m/s

Measurement technique: Single-sensor hot-wire probe; end-flow x-wire probe; both probes mounted on front wall of test section and traversed channel

Data-reduction technique: Mean velocity measured using integrating digital voltmeter; total fluctuating velocity measured by true rms voltmeter. Phase-averaged perturbation velocities and Reynolds stress amplitude and phase were obtained by cross-correlation of input signal with a pulser reference; a cosine curve was fitted to the resultant correlation, and the magnitude and phase were obtained by curve fit. Thus, first-harmonic periodic data were reported in the referenced report although ensemble averaging was used to obtain the original data.

Nominal test conditions: $U_0 = 6.675$ m/sec; $f = 24$ Hz; $Re_{d/2} = 13,850$; $U_1 = 2.4\%$, 3.6%

Availability of data:

Graphic data presented in report:

For $U_1 = 2.4\%$, $f = 24$ Hz: $u_p(A, \phi)$, $R_{11p}(A, \phi)$ vs y/δ

For $U_1 = 3.6\%$, $f = 24$ Hz: \bar{u} , $\sqrt{u'^2}$, \bar{R}_{11} , \bar{R}_{12} , \bar{R}_{22} vs y/δ

$u_p(A, \phi)$, $R_{11p}(A, \phi)$, $R_{12p}(A, \phi)$, $R_{22p}(A, \phi)$, $v_p(A, \phi)$ vs y/δ

For $U_1 = 3.6\%$, $f = 40$ Hz: $u_p(A, \phi)$, $R_{11p}(A, \phi)$ vs y/δ

Data on magnetic tape (supplied by authors):

\bar{u} , $\sqrt{u'^2}$, \bar{R}_{11} vs y , $U_0 = 6.68$ m/sec, $f = 0$

$u_p(A, \phi)$, $R_{11p}(A, \phi)$ vs y , $U_0 = 6.68$ m/sec, $f = 24$ Hz, $U_1 = 3.68\%$

\bar{R}_{11} , \bar{R}_{22} , $v_p(A, \phi)$, $R_{12p}(A, \phi)$, $R_{22p}(A, \phi)$ vs y , $U_0 = 6.68$ m/sec, $f = 24$ Hz, $U_1 = 3.68\%$

$u_p(A, \phi)$, $R_{11p}(A, \phi)$ vs y , $U_0 = 6.68$ m/sec, $f = 40$ Hz, $U_1 = 3.85\%$

Comments by authors: This is a one-laboratory one-investigator experiment. The tabulated data were obtained by measurements from plots in the referenced report. The authors have established that over the range of measurement the periodic velocity data were independent of x and z , and that the data were repeatable over different runs. Note that for the phase data, the relative phases are important, not the absolute values.

Comments by LWC: This experiment documents the response of a fully developed turbulent boundary layer to the imposition of fluctuations of periodic nature. The perturbation velocity has a slug-flow character over most of the channel with a Stokes layer near the walls. The nature of the Stokes layer changed significantly as the frequency was increased. The high-frequency case coincides with the bursting frequency, and several changes occurred as compared to the low-frequency data. The authors conclude that the thickness and the structure of the Stokes layer is strongly dependent on the turbulence dynamics.

Related references: None

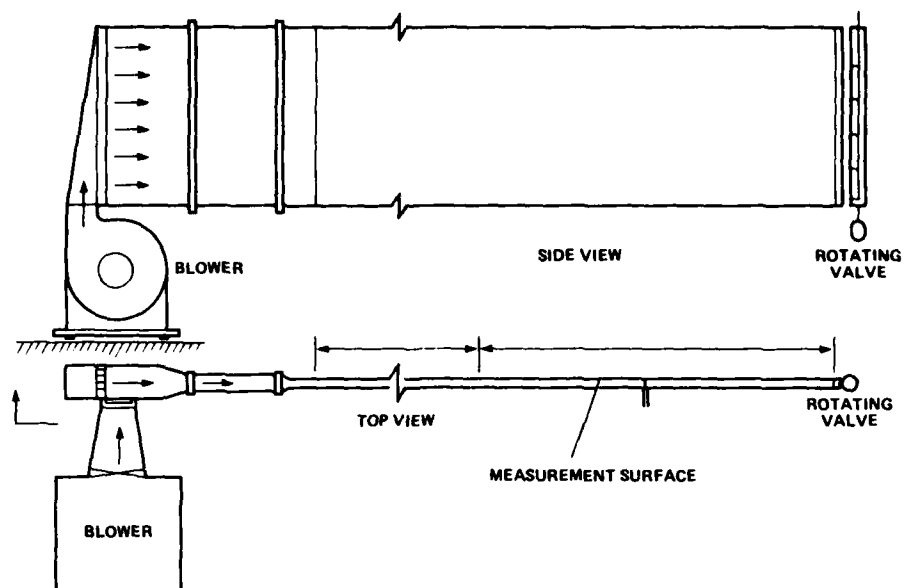


Figure 2 Oscillating flow facility - ACHARYA

Flow title: BINDER

Flow type: Class B, fixed flat surface, zero pressure gradient, boundary layer

Participating research personnel: G. Binder and J. L. Kueny

Primary reference: Measurement of the Periodic Velocity Oscillations Near the Wall in Unsteady Turbulent Boundary Layers. Binder and Kueny, 1981.

Facility:

Location: Institute de Mecanique de Grenoble, Grenoble, France

Apparatus: Water channel; no diagram available at date of publication

Test section: Height 100 mm; span 1000 mm; length 2600 mm

Oscillation mechanism: Oscillating piston in settling chamber

Pressure gradient mechanism: None

Measurement surface: Floor of channel

Trip: Not specified

Wall boundary-layer control: Not specified

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: For amplitude, U_1 , $\pm 2.5\%$; for phase, ϕ , $\pm 1.1^\circ$

Measurement technique: Laser velocimeter with frequency counter

Data-reduction technique: Data were recorded on magnetic tape, then ensemble averages were prepared on computer, 100 points per cycle, 100-400 samples per point

Nominal test conditions: $U_0 = 17.5$ cm/sec; $Re_x = 4.4 \times 10^5$; $U_1 = 5.6\%$; $\omega = 6.4, 57$ rad/sec; $X_0 = 2.4$ m; $u^* = 0.80$ cm/sec

Availability of data:

Graphic data presented in report: $u_p(A, \phi)$ vs y^+ in wall region for $\omega = 6.4, 57$ rad/sec

Data on magnetic tape: None (digital data not yet available)

Comments by LWC: The unsteady turbulent boundary layer behavior very close to the wall ($0 < y^+ < 30$) was studied. The primary result is that the wall velocity behavior appears to follow the laminar Stokes layer at high frequency (showing a 45° phase shift)

Related references: Binder and Favre-Marinet (The present experiment supersedes Binder and Favre-Marinet; the authors state that the earlier data are incorrect, because of laser measurement problems.)

Flow title: BREMBATI

Flow type: Class B, fixed flat surface, nonzero pressure gradient, boundary layer

Participating research personnel: F. Brembati

Primary reference: An Investigation of an Unsteady Turbulent Boundary Layer. Brembati, 1975

Facility:

Location: von Karman Institute, Rhode Saint Genese, Belgium

Apparatus: Open return wind tunnel (see Fig. 3)

Test section: $18 \times 36 \times 120$ cm

Oscillation mechanism: Flexible Plexiglas plate installed in ceiling of tunnel and deformed into and out of the test section sinusoidally

Pressure gradient mechanism: Same as oscillation mechanism

Measurement Surface: Plexiglas plate with elliptical leading edge mounted in test section

Trip: Wire, located 5 cm from leading edge

Wall boundary-layer control: None

Natural frequency: 19 Hz

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Three profiles, measured at centerline, and at 5 cm right and left centerline

Measurement accuracy: Not specified

Measurement technique: Hot-wire anemometer for ensemble average of instantaneous data; pitot-static and hot-wire anemometer for steady data. The ensemble-averaging technique used a very slow continuous traverse of the profile (1 mm/min) to permit rms meter averaging of the data, sampling the signal at a preselected phase angle during each cycle. In regions of high gradients, the hot-wire probe was held fixed during sampling process.

Data reduction technique: The data were ensembled averaged on-line using an rms meter at predetermined phase angles

Nominal test conditions: $U_0 = 16$ m/sec; $U_1 = 5\%$; $f = 10, 15$ Hz

Availability of data:

Graphic data presented in report:

\bar{u} vs y , $f = 0$, $x = 0.61, 0.78, 0.91$ m; $\phi_0 = 0^\circ, 90^\circ, 180^\circ$

$\langle u \rangle$ vs y , $f = 10, 15$ Hz; $x = 0.61, 0.78, 0.91$ m; ϕ_0 at 45° intervals

$\langle u' \rangle$ vs y , $f = 0$; $x = 0.61$; $\phi_0 = 0^\circ, 90^\circ, 180^\circ$

$\langle u' \rangle$ vs y , $f = 10, 15$ Hz; $x = 0.61$ m; ϕ_0 at 45° intervals

δ , δ^* , θ , H , U_e , U^* ; $f = 0$; $x = 0.61, 0.78, 0.91$ m; $\phi_0 = 0^\circ, 90^\circ, 180^\circ$

$\langle \delta \rangle$, $\langle \delta^* \rangle$, $\langle \theta \rangle$, $\langle H \rangle$, $\langle U_e \rangle$, $\langle U^* \rangle$; $f = 10, 15$ Hz; $x = 0.61, 0.78, 0.91$ m; ϕ_0 at 45° intervals

u/u^* vs $\log y u^*/\nu$; $f = 0$; $x = 0.61, 0.78, 0.91$ m; $\phi_0 = 0^\circ, 90^\circ, 180^\circ$

$f = 10, 15$ Hz; $x = 0.61, 0.78, 0.91$ m; ϕ_0 at 45° intervals

Data on magnetic tape: None (digital data no longer exist)

Comments by LWC: This experiment measured the boundary layer under an oscillatory pressure gradient created by sinusoidal flexing of the upper wall of the test section. The author observed that the steady and unsteady profiles agree with the log-law profile for the sublayer and inner layer of the test boundary layer. The boundary-layer thickness (δ), displacement thickness (δ^*), and momentum thickness (θ) show significant variations with x location, but δ^*/δ and θ/δ become much less dependent on the x coordinate.

Related references: None

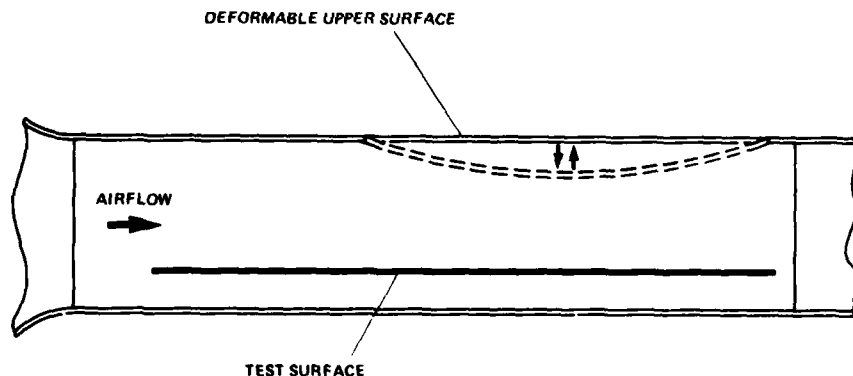


Figure 3 Oscillating flow facility - BREMBATI

Flow title: COUSTEIX (I)

Flow type: Class A, fixed flat surface, zero pressure gradient, boundary layer

Participating research personnel: J. Cousteix, A. Desopper, and R. Houdeville

Primary reference: Experimental Analysis of Average and Turbulent Characteristics of an Oscillatory Boundary Layer. Houdeville, Desopper, and Cousteix, 1976

Facility:

Location: ONERA-CERT/DERAT, Toulouse, France

Apparatus: Open-return wind tunnel; blower downstream of test section

Test section: 100 mm x 110 mm rectangular cross-section (see Fig. 4)

Oscillation mechanism: Rotating vane downstream of test section

Pressure-gradient mechanism: None

Measurement surface: Floor of tunnel

Trip: None

Wall boundary-layer control: None

Natural frequency: 40 Hz

Maximum wall deflections: Not specified

Positional accuracy: x, 1 mm; y, 0.02 mm

Free-stream turbulence: $\approx 1\%$

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Hot-wire anemometer, one wire in free stream, one wire traversing boundary layer

Data-reduction technique: Ensemble average (600 cycles); time average

Nominal test conditions:

$$U_0 = 85 \text{ m/sec}; U_e = U_0 (1 + U_1 \sin \omega t)$$

$$U_1 = 32.9\%$$

$$f = 40 \text{ Hz}$$

$$S = \omega \delta_0 / \bar{U}_e = 3.7 \times 10^{-3}$$

Availability of data:

Graphic data in report:

 $\langle U_e \rangle$ vs (t/T) $\langle u \rangle$ vs (t/T) , seven y positions, x = 210 mm \bar{u}/\bar{U}_e , $\bar{u}_{p1}/\bar{u}_{p1e}$, ϕ vs y, x = 210 mm $\langle u \rangle$ vs y/δ^* , four ϕ_0 , x = 210 mm $\langle u \rangle$, $\langle u'^2 \rangle$ vs (t/T) , five y positions, x = 210 mm $\langle u'^2 \rangle$ vs y/δ^* , four ϕ_0 , x = 210 mm

probability density, flatness factor at five y positions

Data on magnetic tape (supplied by authors):

 $\langle U_e \rangle$ vs (t/T) , nine x stations $\langle u \rangle$, $(\langle u'^2 \rangle)^{1/2}$ vs (t/T) , 24 y stations, x = 0, 70, 140, 210 mm

Comments by LWC: This was the first experiment published by the ONERA/CERT/DERAT group. It is a preliminary study and no boundary-layer trip or sidewall control was used. However, the data are useful for studying relatively high-velocity flat-plate flow, especially when compared with their second experiment. The authors note that although this flow may have reversed near the wall, no reversal was actually detected.

Related references (Experiment I): Cousteix, Desopper, and Houdeville, 1976; Cousteix, Houdeville, and Desopper, 1976; Houdeville, Desopper, and Cousteix, 1977

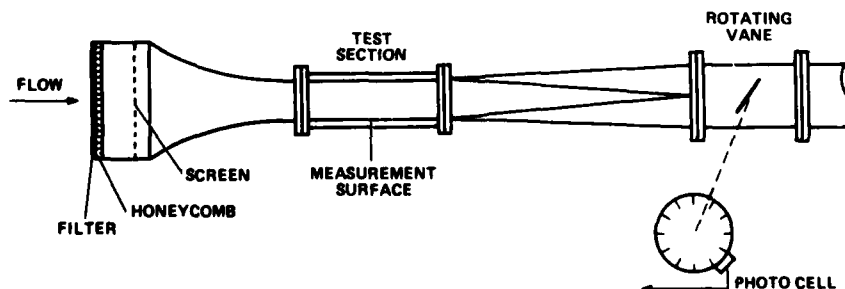


Figure 4 oscillating flow facility - COUSTEIX I and II

Flow title: COUSTEIX (II)

Flow type: Class A, fixed flat surface, zero pressure gradient, boundary layer

Participating research personnel: J. Cousteix, R. Houdeville, and A. Desopper

Primary reference: Structure and Development of a Turbulent Boundary Layer in an Oscillating External Flow. Cousteix, Desopper, and Houdeville, 1977

Facility:

Location: ONERA-CERT/DERAT, Toulouse, France

Apparatus: Open return wind tunnel (see Fig. 4)

Test section: 100 x 110 mm rectangular cross section

Oscillation mechanism: Rotating vane downstream of test section

Pressure gradient mechanism: None

Measurement surface: Floor of wind tunnel

Trip: None

Wall boundary-layer control: None

Natural frequency: 43 Hz

Maximum wall deflection: Not specified

Positional accuracy: x, 1 mm; y, 0.02 mm

Free-stream turbulence: $\pm 1\%$

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Hot-wire anemometer; one wire in free stream, one traversing boundary layer; x-wire used for Reynolds stress measurement

Data-reduction technique: Ensemble average on computer (96 samples per cycle; 600 cycles in average)

Nominal test conditions: $u_e = U_0(1 + U_1 \sin \omega t)$; $U_0 = 33.62$ m/sec at $x = 0$; $U_1 = 37\%$; $f = 43$ Hz;
 S (at $x = 0$) = $\omega \delta_m^*/u_{e_m} = 12.7 \times 10^{-3}$

Availability of data:

Data presented in report: $\Delta \phi_e$, \bar{u}_e/\bar{u}_{e0} , for $0 < x < 200$ mm ($()_0$ is at $x = 0$)

The following data are presented for $x = 210$ mm only:

\bar{u}_p/\bar{u}_{pe} , $\Delta u/\Delta u_e$, ϕ vs y

$\langle u \rangle/\langle u_e \rangle$, $\sqrt{\langle u'^2 \rangle}$, $\langle u'v' \rangle$ vs y for four ϕ_0

$\langle H \rangle$ vs (t/T)

$\langle u'^2 \rangle/\langle u'^2 \rangle_m$, $\langle u \rangle/u_m$ vs (t/T) , five y positions

$\langle u'v' \rangle/\sqrt{\langle u'^2 \rangle \langle v'^2 \rangle}$ vs (t/T) , five y positions

$-\langle u'v' \rangle/(\partial u/\partial y)$ vs (t/T) , five y positions

$\langle \delta^* \rangle$, $\langle \theta \rangle$ vs (t/T)

$\langle u \rangle/\langle u_e \rangle$ vs (y/δ_1) , six (t/T) positions

$\langle u'v' \rangle/u_e^2$ vs (y/δ^*) , six y positions

Data on magnetic tape (supplied by authors):

$\langle u_e \rangle$ vs (t/T) , for seven x stations

Single-wire data: $\langle u \rangle$, $\sqrt{\langle u'^2 \rangle}$ vs (t/T) for 21 y positions, $x = 0, 70, 140, 210$ mm

X-wire data: $\langle u_A \rangle$, $\langle u_B \rangle$, $\sqrt{\langle u'^2 \rangle}$, $\sqrt{\langle v'^2 \rangle}$, $\langle u'v' \rangle$ for 20 y positions, $x = 0, 70, 140, 210$ mm

Comments by authors: The experiments in the 0.1 m x 0.11 m wind tunnel are preliminary experiments. The distance between the utmost measurement stations is not great enough to check (precisely) a calculation method. A new set of experiments over a flat plate is in progress, with $\omega x/U_0$ varying between 0.2 and 18. In this new experiment, a great number of velocity profiles have been measured to define precisely the response of the turbulent boundary layer to the perturbation induced by the oscillation of the external velocity. A periodicity equal to 5 is observed in Strouhal number, which implies that measurements corresponding to variation of the Strouhal number of the order 0.5 has to be done. Although very detailed measurements at a given station are of great interest, we think that it is absolutely necessary to do measurements along the flow direction to obtain a better understanding of the response of the boundary layer.

In all our experiments, there are no pressure taps on the surface in which the boundary layer develops to avoid local perturbation of the velocity profiles due to the oscillating jets coming from the cavities under the pressure taps.

Comments by LWC: This experiment extends the ONERA flat-plate study to higher Strouhal number and includes shear stress for the first time. In this experiment no trip was used. The authors note that the y -position of maximum phase lead is closer to the surface in this experiment than in the first flat-plate study; a comparison is presented in Cousteix, Houdeville and Desopper, 1977a.

Related references (Experiment II): Cousteix, 1979

Flow title: COUSTEIX (III)

Flow type: Class A, fixed flat surface, adverse pressure gradient, boundary layer

Participating research personnel: J. Cousteix, R. Houdeville, and M. Raynaud

Primary references: (1) Unsteady Boundary Layer Experiment and Calculations Performed at ONERA-CERT. Cousteix and Houdeville, 1979; (2) First Results of a Study on Turbulent Boundary Layers in Oscillating Flow with a Mean Adverse Pressure Gradient. Houdeville and Cousteix, 1979

Facility:

Location: ONERA-CERT/DERAT, Toulouse, France

Apparatus: Open return wind tunnel (blower downstream of test section); see Fig. 5

Test section: 160 x 220-mm constant area duct followed by 400-mm adverse pressure gradient region

Oscillation mechanism: Rotating vanes downstream of test section

Pressure-gradient mechanism: Adjustable airfoil in middle of test section

Measurement surface: Floor of wind tunnel

Trip: Sandpaper placed in collector 110 mm upstream of test section (105 mm long)

Wall boundary-layer control: Sidewall suction to prevent separation of lateral wall boundary layers; upper wall suction to avoid blockage

Natural frequency: 38 Hz

Maximum wall deflection: No detectable deflection by wall streamline visualization in the axial region 100 mm width

Positional accuracy: Probe is isolated from tunnel; no motion of tunnel wall detected; x, 1 mm; y, 0.02 mm

Free-stream turbulence: 1 to 2% depending on x

Verification of two-dimensionality: Two-dimensional flow for 600 cm; method not specified

Measurement accuracy: Velocity: $\pm 1\%$ (hot-wire or LDV)

Measurement techniques: For nonreversing flow, constant-temperature hot-wire anemometer using both straight and cross-wire probes; for reversing flow, one-channel laser anemometer with Bragg cell

Data-reduction techniques: Ensemble averages for 600 or 1200 cycles of data, 48 samples per cycle, performed on computer

Nominal test conditions: One mean velocity (30 m/sec), one frequency (38 Hz), x range from 25 mm to 600 mm, u_e varies from 30 m/sec to 20 m/sec as $f(x)$

x(mm)	U_1	$10^{-6} \times \frac{x u_e}{\nu}$	$\frac{\omega x}{U_0}$	$f_t \left(\frac{\sqrt{u'^2_{max}}}{\delta} \right)$
100	19	0.74	3.0	350
240	16	0.91	4.6	300
390	16	1.00	7.0	230
604	13	1.15	10.0	70

Availability of data:

Graphic data presented in reports:

 \bar{u}_e/U_0 , $\Delta u_e/U_0$, ϕ , for $-25 \text{ mm} < x < 60 \text{ mm}$ \bar{u}/\bar{u}_e , $\Delta u/\Delta u_e$, $\Delta \phi(\phi_u - \phi_{u_e})$ vs y for x = 100, 190, 290, 340, 390 mm $\langle \delta^* \rangle$, $\langle H \rangle$ vs (t/T) for x = 100, 290, 340, 435, 556, 604 mm $\langle u/u_e \rangle$, $\sqrt{\langle u'^2 \rangle}/u_e$ vs y at five (t/T) positions, x = 604 mm $\langle u'^3 \rangle/\langle u'^2 \rangle^{3/2}$; $\langle u'^4 \rangle/\langle u'^2 \rangle^2$ vs y at three (t/T) values, x = 604 mmProbability, $P[u \leq 0]$ vs y at seven (t/T) values, x = 604 mm $\langle u'v' \rangle/u_e^2$ vs y at six (t/T) values, x = 390 mm $\langle u'v' \rangle/\langle \bar{u}'\bar{v}' \rangle$, $\langle u'v' \rangle/(\langle u'^2 \rangle \langle v'^2 \rangle)^{1/2}$, $\langle v'^2 \rangle/\langle u'^2 \rangle$ vs (t/T) for three y stations, x = 390 mm

Data on magnetic tape (supplied by authors):

 $\langle u_e \rangle$ for 48 ϕ_0 , for x positions every 25 mm, x = 27 to 123; 145 to 595 mm $\langle u \rangle$, $\langle u'^2 \rangle$ for 48 ϕ_0 , 25 y positions at x = 48, 100, 150, 196, 240, 290, 340, 390, 435, 506, 556, 604 mm $\langle u_A \rangle$, $\langle u_B \rangle$, $\langle u'^2 \rangle$, $\langle v'^2 \rangle$, $\langle u'v' \rangle$, for 48 ϕ_0 , 19 y positions, at x = 196, 290, 390, 435, 506, 556, 604 mm

Comments by authors: In the first 200 mm, the flow is affected by the acceleration of the external velocity due to the obstruction produced by the central airfoil and therefore does not correspond exactly to a flat-plate configuration. The evolution observed shows an oscillation of the boundary-layer parameters (e.g., θ or δ^*) as the Strouhal number increases up to 10. The response looks like what is obtained over a flat plate; the effect of the adverse pressure gradient is to increase the amplitude of the oscillation.

The occurrence of harmonics in δ^* may be due to a traveling wave with a celerity equal to $0.5 \bar{u}_e$ which affects the velocity profiles. This wave is probably related to the occurrence of a vortex-like structure which appears at some instants as revealed by the evolution of the streak lines. These lines are obtained from the estimation of the u component deduced from the continuity equation. The results are presented in a movie which has been produced at ONERA.

Comments by LWC: This experiment is part of a series of carefully documented unsteady turbulent boundary-layer experiments performed at ONERA/CERT. Because of tunnel limitations, only one frequency and one amplitude have been performed. The flow is flat-plate zero pressure gradient up to $x = 200$ mm, $\Delta u < 10\% \Delta u_e$. The flow then enters the adverse pressure gradient region, and at $x = 390$ mm, $\Delta u \approx 60\% \Delta u_e$. The authors indicate that the mean-velocity profiles are the same as steady state, but the relative amplitude of the boundary-layer response is significantly different. They establish the existence of a log region near the wall (Houdeville and Cousteix, 1978). The ensemble-averages of displacement thickness, and shape factor are sinusoidal at low x stations, whereas unsteady effects become more important near flow reversal. Higher harmonics appear in δ^* and H downstream of 435 mm, but are no longer present at 604 mm. They observe that δ^* varies by a factor of two while no change is apparent in δ .

Related references (Experiment III): Cousteix, Houdeville, and Raynaud, 1979; Cousteix, 1979a

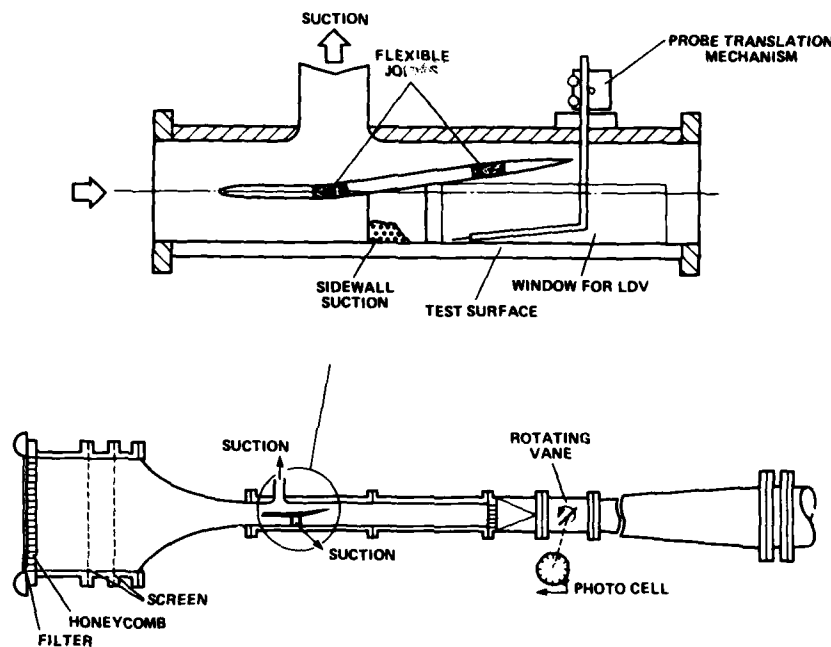


Figure 5 Oscillating flow facility - COUSTEIX III

Flow title: EVANS

Flow type: Class B, fixed airfoil surface, adverse pressure gradient, boundary layer

Participating research personnel: R. L. Evans

Primary reference: Boundary-Layer Development on an Axial-Flow Compressor Stator Blade. Evans, 1978

Facility:

Location: Whittle Laboratory, Cambridge University, England

Apparatus: Large, low-speed, single-stage experimental compressor; no diagram available at date of publication

Test section: Stator stage of compressor, hub diameter of 61 cm (24 in.) and tip diameter of 152.4 cm (60 in.)

Oscillation mechanism: Compressor rotor ahead of test surface

Pressure gradient mechanism: Stator blade, C-4 section, 30.5-cm (12-in.) chord

Measurement surface: Upper surface of stator blade

Trip: Wire mounted at 10% chord

Wall boundary-layer control: Not specified

Natural frequency: Not specified

Maximum surface deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Traversing hot-wire anemometer built into a device that is brought into contact with the stator blade; includes a vertical motion positioner for the hot-wire surveys.

Data-reduction technique: The hot-wire signal is linearized and fed directly into an rms meter, a dc voltmeter, and into a computer. Ensemble averages of 512 points per cycle were obtained. Data were stored on magnetic tape. Total cycles averaged was 500.

Nominal test conditions: $Re_c = 5 \times 10^5$; flow coefficient = 0.51, resulting in a mean incidence (i) = 3.5° ; rotor speed = 650 rpm, effective unsteady frequency = 240 Hz; $U_0 \approx 80$ ft/sec

Availability of data:

Graphic data presented in reports:

C_p vs x/c , $i = 0.8, 3.5, 4.4^\circ$

(\bar{u}/\bar{u}_e) vs y , $x/c = 0.3, 0.5, 0.7, 0.8$, $i = 2.5^\circ$

δ^* , H , C_f vs x/c , $Re = 5 \times 10^5$;

$A(u)/A(u_e)$ vs y , $x/c = 0.3, 0.5, 0.7$; $i = 3.5^\circ$

$\langle u \rangle$ at $\phi_0 = 0^\circ, 180^\circ$; $x/c = 0.3, 0.5, 0.7$, $i = 3.5^\circ$

Data on magnetic tape: None; digital data no longer exists

Comments by LWC: It is unfortunate that the ensemble-averaged data for this experiment no longer exist. Even so, the limited data that are available in the referenced report show some interesting trends. The author notes that although the mean-velocity profiles appear to indicate fully developed turbulent flow, ensemble-averaged instantaneous profiles show the boundary layer to be highly unsteady and transitional over much of the blade chord. The flow in this experiment is relatively low Reynolds number, and turbulent flow occurs only over part of the cycle. Very strong phase shifts are noted but are attributed to the transitional nature of the boundary layer.

Related references: Evans, 1973, 1975, 1976, 1978

Flow title: JOHNSON

Flow type: Class A, fixed flat surface, zero pressure gradient, zero mean velocity, boundary layer

Participating research personnel: I. G. Jonnson and N. A. Carlsen

Primary reference: Experimental and Theoretical Investigations in an Oscillatory Turbulent Boundary Layer. Jonnson and Carlsen, 1976

Facility:

Location: Institute of Hydrodynamics and Hydraulics Engineering, Technical University of Denmark, Lyngby, Denmark

Apparatus: Oscillating water tunnel, zero mean velocity (see Fig. 6)

Test section: 10 m length, 30 cm height, 40 cm width

Oscillation mechanism: Test-section entrance and exit connected to large riser chambers, one open, one closed. Closed riser connected to cylinder and piston that sinusoidally cycles the water level

Pressure gradient mechanism: None

Measurement surface: Floor of test section

Trip: Not specified

Wall boundary-layer control: None

Natural frequency: 0.105 Hz

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Velocities measured with a micropropeller. Angular velocity of aluminum propeller is registered by a photodiode and an electronic counter.

Data reduction technique: Data are ensemble-averaged for 24 points within each cycle; 25 to 50 cycles are averaged

Nominal test conditions: Two tests were performed:

	Test 1	Test 2
Wave period, sec	8.39	7.20
Free-stream amplitude, cm	285	179
Amplitude of mean free-stream velocity cm/sec	211	153
Reynolds number based on amplitude	6×10^6	2.7×10^6

Availability of data:

Data presented in report:

$\langle u \rangle$ for 20 y positions, 24 (t/T) positions, Tests 1 and 2, tabular form

$\langle \tau/\rho \rangle$ for 20 y positions, 24 (t/T) positions, Tests 1 and 2, tabular form

Local $\langle \epsilon \rangle_m$, 20 y positions, 24 (t/T) positions, Tests 1 and 2, tabular form

$\langle u \rangle$ at two y positions, graphic form, Tests 1 and 2

$\langle u \rangle$ vs y for five t/T positions, Tests 1 and 2

Data on magnetic tape (supplied by authors):

$\langle u \rangle$ for 20 y positions, 24 phase positions, Tests 1 and 2

$\langle \tau/\rho \rangle$ for 20 y positions, 24 phase positions, Tests 1 and 2

$\langle \epsilon \rangle_m$ for 20 y positions, 24 phase positions, Tests 1 and 2

Comments by LWC: This experiment was designed to study the behavior of turbulent flow near the floor of the ocean. It is one of the few experiments with zero mean velocity. The authors conclude that a logarithmic velocity distribution was detectable for these flows.

Related references: Jonnson, 1976, 1977, 1978a, 1978b

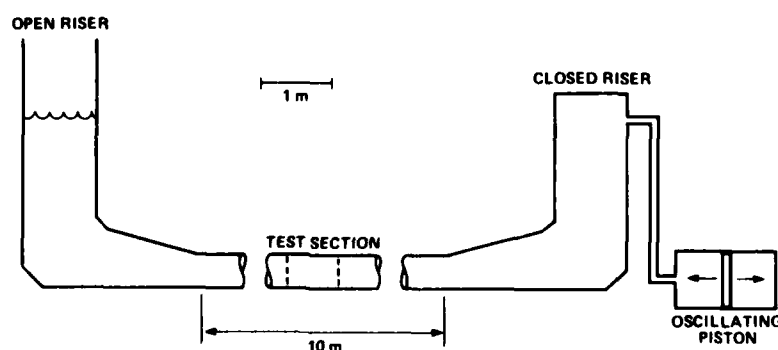


Figure 6 Oscillating flow facility - JOHNSON

Flow title: KARLSSON

Flow type: Class A, fixed flat surface, zero pressure gradient, boundary layer

Participating research personnel: S. K. F. Karlsson

Primary reference: An Unsteady Turbulent Boundary Layer. Karlsson, 1958

Facility:

Location: Department of Aeronautics, Johns Hopkins U., Baltimore, Md.

Apparatus: Open return wind tunnel (see Fig. 7)

Test section: 20 ft length, 12 x 18 in. at start, 13 x 19 in. at end

Oscillation mechanism: Rotating vanes downstream of test section (one vane rotated at twice the speed of others to remove second harmonic)

Pressure gradient mechanism: None

Measurement surface: Lower wall of test section

Trip: 0.25-in. rods perpendicular to surface in zig-zag pattern

Wall boundary-layer control: None; walls adjusted for zero pressure gradient

Natural frequency: 24 Hz for standing sound wave

Maximum wall deflection: 0.001 in. (reinforced walls)

Positional accuracy: ± 0.005 in. ($y = 0$ to 0.20); ± 0.001 in. ($y = 0.020$ to 1.0 in.); ± 0.005 in. (y above 1.0 in.)

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: $\pm 2\%$ in mean-velocity profile

Measurement technique: Dual hot-wire probes, one stationary in free stream, one traversing the boundary layer. Calibration performed using pitot-static probe and manometer board

Data-reduction technique: Analog data analysis including phase shifter to obtain in- and out-of-phase components of velocity. Only first harmonic component was obtainable; all higher harmonic content is included in the turbulence measurements

Nominal test conditions: $U_0 = 17.5$ ft/sec (0.33 Hz and quasi-steady cases were run at 15 ft/sec); $\delta = 3$ in.; $Re_{\delta^*} = 3.6 \times 10^5$; $C_f = 0.0034$ (by Clauser "law of the wall"); $f = 0$ to 48 Hz; $U_1 = 8$ to 34%; $X_0 = 98$ in.

Availability of data:

Graphic data presented in report: \bar{u}/\bar{u}_e , $u_p/u_{pe} \sin \phi$, $\sqrt{r^2}/\bar{u}_e$ vs y presented for:

$f = 0.0$ Hz, $U_1 = 0.0, 30.0\%$ (quasi-steady)

$f = 0.33$ Hz; $U_1 = 14.7, 20.2, 29.2\%$

$f = 0.66$ Hz; $U_1 = 11.2, 14.9, 34.0\%$

$f = 1.0$ Hz; $U_1 = 10.7, 19.5, 35.2\%$

$f = 1.33$ Hz; $U_1 = 13.0, 21.5, 34.4\%$

$f = 2.0$ Hz; $U_1 = 8.1, 17.6, 28.6\%$

$f = 4.0$ Hz; $U_1 = 6.2, 13.6, 26.4\%$

$f = 7.65$ Hz; $U_1 = 7.3, 12.7, 29.7\%$

$f = 48.0$ Hz; $U_1 = 34.0\%$

Data on magnetic tape: All the data listed above have been tabulated from the author's original data records, except the $f = 0$, and $f = 48$ Hz cases, which have been re-digitized from enlarged versions of the graphs presented in the thesis.

Comments by LWC: This experiment was the first to document the behavior of an unsteady turbulent boundary layer on the flat plate. It is still the most comprehensive set of data concerning amplitude and frequency effects on flat-plate turbulent boundary layers in existence. The data reduction techniques are less sophisticated than present day methods, but the results are of primary value for comparison purposes.

The data are presented in amplitude form, mean amplitude, then in-phase and out-of-phase first-harmonic amplitudes are given. The author notes that flow reversal was observed near the wall for certain conditions at high amplitude but this information is not representable in the data format used to present the results. The author concludes that there is no systematic variation in the mean-velocity profiles because of fluctuation frequency or amplitude. There is a detectable effect of frequency on the in-phase component of amplitude, bringing the maximum value closer to the wall as the frequency increases. A lag appears in the outer portion of the boundary layer at 1 Hz, but gradually decreases as the frequency is increased. A positive phase shift is observed near the wall, reaching 35° for 7.65 Hz at $y = 0.010$ in.

Related references: Karlsson, 1959

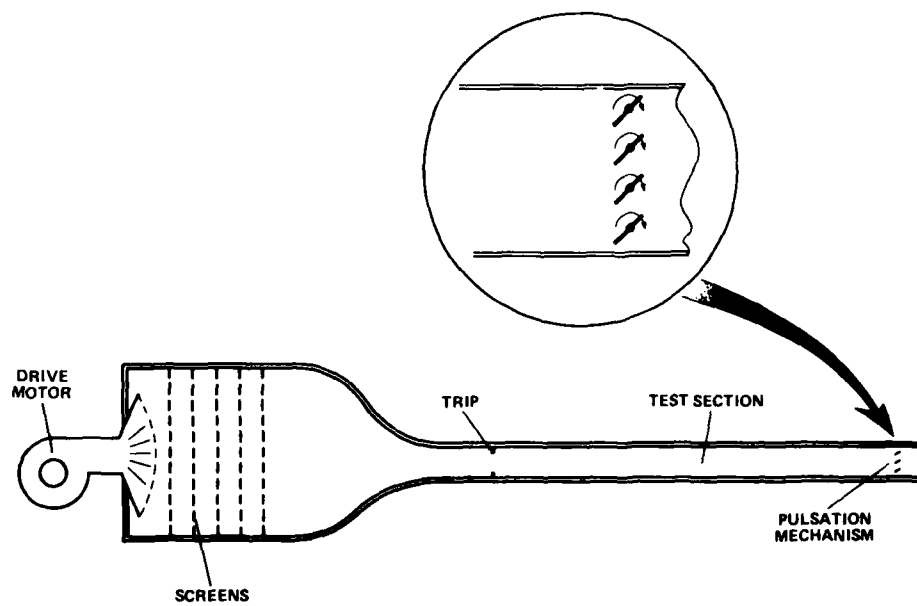


Figure 7 Oscillating flow facility - KARLSSON

Flow title: KENDALL

Flow type: Class B, waving surface, zero pressure gradient, boundary layer

Participating research personnel: J. M. Kendall

Primary reference: The Turbulent Boundary Layer over a Wall with Progressive Surface Waves. Kendall, 1970

Facility:

Location: Jet Propulsion Laboratory, California Inst. of Tech., Pasadena, Calif.

Apparatus: Low-turbulence wind tunnel (diagram not available at date of publication)

Test section: 2 ft square by 9 ft long

Oscillation mechanism: A wavy wall comprising the last 4 ft of the test section floor. This wavy wall was made of 0.25-in. neoprene rubber sheet constrained to form 12 sinusoidal waves which travel with a speed $0.3 < |C| < 3.0$ m/sec

Pressure gradient mechanism: None

Trip: Installed at the leading edge of the test section floor

Wall boundary-layer control: None

Natural frequency: Not specified

Maximum wall deflection: Not applicable (wall is driving mechanism)

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Surface pressure measurements were made by mounting tubing on the flexible surface and connecting by flexible connections to pressure transducers. The velocity was measured using one hot-wire probe on a traverse independent of the movable surface, and a second probe mounted to the waving wall. Pressure measurements were made at four x locations, and velocity measurements only at one x location. An inclined probe was also mounted on the traversing mechanism. A wall stress meter was also used.

Data reduction technique: The hot-wire data were ensemble-averaged using a 512-channel ensemble-averaging system; between a few hundred to a few thousand cycles were averaged.

Nominal test conditions: wave length: 4 in.; wave speed $|C|$: $0.3 < |C| < 3$ m/sec; wave amplitude: 0.125 in.; free-stream velocity: $U_0 = 0$ to 16 m/sec; x locations for pressure: 6.5, 18.5, 30.5, 42.5 in.; $U_1 = 7.5\%$

Availability of data:

Graphic data presented in report:

C_p vs (t/T) , $U_\infty = 3.2, 5.5, 8.0, 10.6$ m/sec

C_p vs C/U_∞ for six U_∞ values

(U/U_∞) vs y for three phases in cycle

u_p/U_∞ vs (t/T) , $U_\infty = 5.5$ m/sec; $C = 3.0$ m/sec; 11 y positions

u_p/U_∞ vs (t/T) ; $C = 3.0$ m/sec; $y = 0.052$ in.; seven U_∞ values

v_p vs (t/T) ; $U_\infty = 5.5$ m/sec; $y = 0.060, 0.240$ in. above crest, four wave speeds

v_p/u_p vs y for six C/U_∞

$\langle u'v' \rangle$ vs (t/T) ; $U_\infty = 5.5$ m/sec; $C = 1.2$ m/sec, 0.060 in. above crest

$\overline{u_p v_p}$ vs y , $C = 3.0$ m/sec for four U_∞ values

$\langle u'v' \rangle$ vs (t/T) at various y locations, three C values

$\langle u'^2 \rangle$ vs (t/T) ; $U_\infty = 5.5$ m/sec; $y = 0.120$ in., three C values

$\langle \tau_w \rangle$ vs (t/T)

Data on magnetic tape: None (digital data no longer exist)

Comments by LWC: This experiment is unusual because the source of the oscillation perturbation came from within the boundary layer. The author notes that these waves strongly modulate the turbulent structure and that the phase of the turbulent stresses varies with wave speed. The perturbation signal is quite small, thus requiring ensemble averages over several thousand cycles. The pressure results appear to depend only on local conditions. If the critical layer lies outside of the laminar sublayer $|\bar{u}_p|$ is much smaller than the local $|u'|$

Related references: None

Flow title: KENISON

Flow type: Class B, fixed flat surface, adverse pressure gradient, traveling wave unsteadiness, boundary layer

Participating research personnel: R. C. Kenison

Primary reference: Measurements of a Separating Turbulent Boundary Layer with an Oscillating Free Stream. Kenison, 1977b

Facility:

Location: Queen Mary College, Mile End Road, U. of London, London, England

Apparatus: Open-return blow-down wind tunnel (see Fig. 8)

Test section: Semi-open (open top and bottom, closed sides); cross section = 1 m wide \times 1.4 m high

Oscillation mechanism: Upper and lower surfaces of nozzle exit are flexible flaps; when deflected simultaneously they induce a traveling vortex pattern which moves down the tunnel

Pressure gradient mechanism: Flat plate 2 m long, 1 m wide, installed at midplane of tunnel. On the upper surface, 1.85 m from leading edge of plate, a slotted spoiler was installed at 50° to horizontal. Slots in spoiler stabilized the wake and reduced the natural unsteadiness of the separated region in steady flow

Measuring surface: The upper surface of the plate used to produce the adverse pressure gradient.

Measurement surface extended 0.3 m into nozzle throat

Trip: A strip of rough paper placed close to the leading edge

Wall boundary-layer control: None specified

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Demonstrated by flow visualization. Chemically reacting mixture painted on model showed good two-dimensionality at steady separation line, and a streaky pattern during oscillation.

Measurement technique: Root-mean-square pressure measurements made using static pressure taps and pressure transducers. Local mean skin-friction measurements were made using Preston tubes both for steady and oscillatory flow. Two hot wires were used, one in a traverse mechanism attached to the model surface, the other used in the free stream to conditionally trigger the data acquisition system.

Data-reduction technique: Measurements by the sampling unit were only made at the forcing frequency. The hot-wire data were passed through a 25-Hz low-pass filter. Samples were taken with eight samples over nine cycles; multiples were taken to produce a sampling rate at 1/8 cycle steps. Signals were then processed by a digital voltmeter and stored digitally. There were 40 cycles averaged to obtain resultant data, which was then Fourier analyzed, retaining only the first harmonic.

Nominal test conditions: $U_0 = 22$ m/sec; $U_1 = 10\%$; $f = 0$ to 6 Hz; $\omega x/u_\infty = 0$ to 3; flap amplitude (A_f) = 25.4, 50.8, 76.2 mm; $U_e(x,t) = U_0(1 + U_{1e}^{i\omega(t-x/c)})$

Availability of data:

Graphic data presented in report:

τ_w vs ϕ_0 for 12 x stations, $f = 2$ to 6 Hz, $A_f = 25.4, 50.8, 76.2$ mm

$|\tau_{wp}|$ vs x for five frequencies, three flap amplitudes

$u_p(A, \phi)$ vs y for nine x stations, five frequencies, $A_f = 76.2$ mm

$H(x), \theta(x), u_{rms}/U_1$ vs x , six frequencies

\bar{u}/\bar{u}_e vs y for eight x stations, $f = 5$ Hz

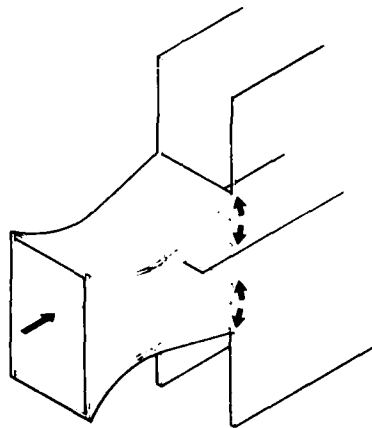
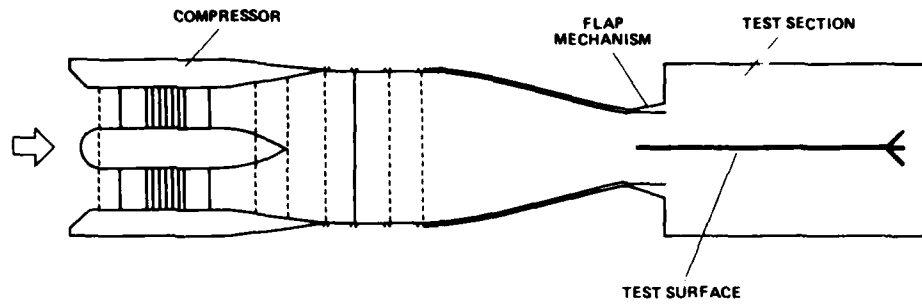
$C_p(x)$ for $f = 0, 2, 6$ Hz

$\Delta C_{p,rms}(x)$ for five frequencies, three flap amplitudes

Data on magnetic tape: None (digital data no longer exist). N.B.: Any proposed re-digitization should be done from original curves - the publicly available microfiche is distorted.)

Comments by LWC: This experiment is part of a series (Patel, 1977; Pericleous, 1977) that utilized the effects of traveling vortices as oscillation producers. Kenison notes that the oscillation does affect the boundary layer near the mean separation line, causing periodic reversal of the flow ahead of the mean line of separation. The measurements were made using a hot wire, so quantitative behavior of separation is not documented. However, the reversed flow is limited to a thin layer and is not detectable in any of the measured profiles, skin friction, etc. Amplitude fluctuations in the boundary layer can exceed those at the edge. There is a phase lag in the unsteady boundary layer that is much larger than that found on the zero pressure gradient case of Patel (1977)

Related references: Kenison, 1977b; Patel, 1975, 1977; Pericleous, 1977



DETAIL OF FLAP MECHANISM

Figure 8 Oscillating flow facility - KENISON

Flow title: LU

Flow type: Class B, fixed surface, fully developed pipe flow

Participating research personnel: F. F. Erian, S. Z. Lu, M. Mohajery, R. J. Nunge

Primary reference: Measurements of Pulsating Turbulent Water Flow in a Tube. Lu, et al., 1973

Facility:

Location: Department of Chemical and Mechanical Engineering, Clarkson College of Technology, Potsdam, N.Y.

Apparatus: Gravity-fed water tunnel (see Fig. 9)

Test section: 2-in. i.d. \times 2.5-in. o.d., acrylic resin tube

Oscillation mechanism: Oscillating pump connected to settling chamber

Pressure-gradient mechanism: None

Measurement surface: Wall of pipe

Trip: 1/16 in. high trip ring

Wall boundary-layer control: None

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of axisymmetry: Not specified

Measurement accuracy: Not specified

Measurement technique: A hot-film probe was used for obtaining mean and fluctuating velocities. A slant wire was tried for Reynolds stress, but was not satisfactory for measurement in water. A pressure transducer was used for measuring mean and fluctuating pressure.

Data-reduction technique: The signal was passed through a low-pass filter for mean velocity, and a high-pass filter for turbulence intensities. The mean pressure was obtained using a low-pass filter. Ensemble-averaged data were obtained, using 10 cycles at the centerline, 20 cycles near the wall.

Nominal test conditions: U_0 : 0.0 to 0.7 cm/sec; Re: 16,000 to 81,600; U_1 : 0.0 to 25%; $\omega'(\omega R^2/\nu)$: 0 to 3130; X_0 : 79 pipe diameters from trip

Availability of data:

Graphic data presented in report:

(1) \bar{u}/\bar{u}_{CL} vs y/R , $\omega' = 0, 3130$, Re = 45,000; $\omega' = 1781$, Re = 81,600

(2) $\Delta u/\bar{u}_{CL}$; $\phi_0 = 180, 240, 300, 360^\circ$ for Re = 81,600, $\omega R^2/\nu = 1291, 1336, 1781, 3130$

Data on magnetic tape: None (digital data not available at time of publication)

Comments by LWC: Authors conclude that long-time average velocity distributions are coincident with steady flow. However, the distribution of the measured pulsating velocity component depends on the dimensionless frequency parameter. At low values of $\omega R^2/\nu$ the unsteady component of velocity shows turbulent-flow-type profiles, while at higher values, the maximum velocity point moves from the centerline toward the wall, and a constant-speed region exists over the central portion of the tube.

Related references: None

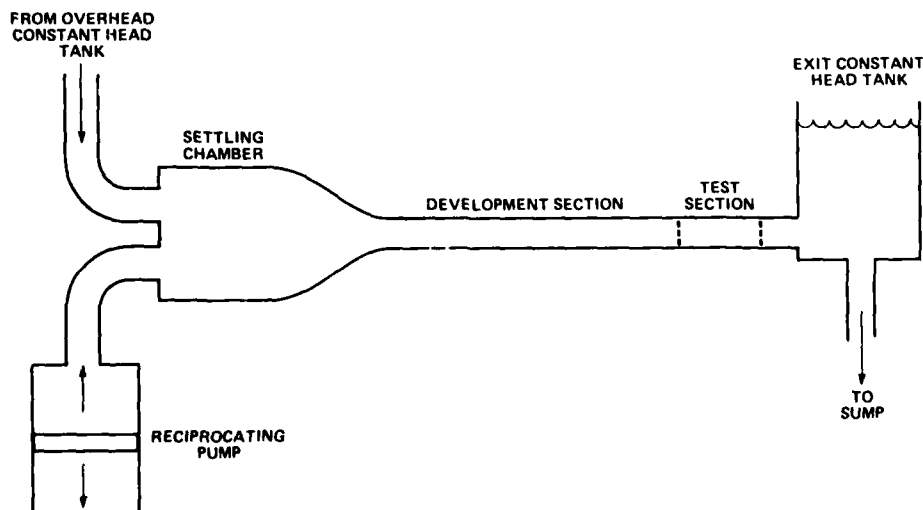


Figure 9 Oscillating flow facility - LU

Flow title: MARVIN

Flow type: Class A, fixed airfoil surface, shock-induced flow oscillation, boundary layer

Participating research personnel: L. L. Levy, Jr., J. G. Marvin, and H. L. Seegmiller

Primary reference: On Turbulence Modeling for Unsteady Transonic Flows, Marvin et al., 1979

Facility:

Location: Ames Research Center, NASA, Moffett Field, Calif.

Apparatus: High-Reynolds-number blow-down wind tunnel

Test section: Rectangular, 38.1 cm by 24.4 cm with shaped upper and lower walls (see Fig. 10)

Oscillation mechanism: Unsteady periodic flow caused by shock-induced separation alternately occurring on upper and lower surface of fixed airfoil

Pressure gradient mechanism: Circular-arc airfoil, 20.34-cm chord, 0.18 thickness ratio, 25.4-cm span

Measurement surface: Upper surface region of airfoil; rear quadrant-wake; upper wall of test section

Trip: None

Wall boundary-layer control: None

Natural frequency: Not applicable

Maximum wall deflection: Not applicable

Positional accuracy: $x/c \pm 0.005$; $y/c \pm 0.002$ Free-stream turbulence: $\langle u'^2 \rangle / U_\infty^2 = 0.01$ Verification of two-dimensionality: Oil flow and lateral surface pressures during steady flow tests at higher and lower M_∞

Measurement accuracy: A few percent up to 20% for velocity and turbulence intensity; no estimate for shear stress

Measurement technique: Laser velocimeter with probe dimensions approximately 0.3 mm diam, 3 mm length. A two-channel synchronized counter system measured velocities of 0.4- μ m diam polystyrene particles introduced in the settling chamber; 2000 data samples were recorded at each spatial station. The pressure signal measured at midchord was used to provide the trigger for conditional sampling of the flow.

Data reduction technique: About 2000 or more data samples were recorded on analog tape at each spatial station. An ensemble average of the conditionally sampled data was performed to obtain instantaneous values for various parameters at selected times within a cycle of oscillation. A movie was made from the results of the ensemble average, and aided in subsequent data analysis.

Nominal test conditions: $M_\infty = 0.76$; $Re_c = 11 \times 10^6$; $f = 185$ Hz; U_1 not specified

Availability of data:

Graphic data presented in reports:

In Marvin et al. (1979):

 $\langle TKE \rangle$, $\langle \tau \rangle$, $\langle u \rangle$ vs y at eight (x/c) stations for four (t/T) values $\langle TKE \rangle$, $\langle \tau \rangle$, $\langle u \rangle$ vs y at four (y/c) stations for three (x/c) values

In Marvin et al. (1980):

 $\langle TKE \rangle$, $\langle \tau \rangle$, $\langle u \rangle$ vs (t/T) at three (x/c) stations for various (y/c) values $\langle \tau \rangle$, $\langle u \rangle$ vs (y/c) at eight (x/c) stations for three (t/T) values

Data on magnetic tape (supplied by authors): Digital data are available for all the cases presented in the reports

Comments by LWC: This experiment used a shock-induced limit-cycle oscillation as the driving mechanism of the unsteady turbulent flow. It is the only well documented transonic unsteady turbulent boundary layer flow that has appeared, and is a very worthwhile contribution to the data bank.

Related references: Marvin et al (1980), Seegmiller et al. (1978)

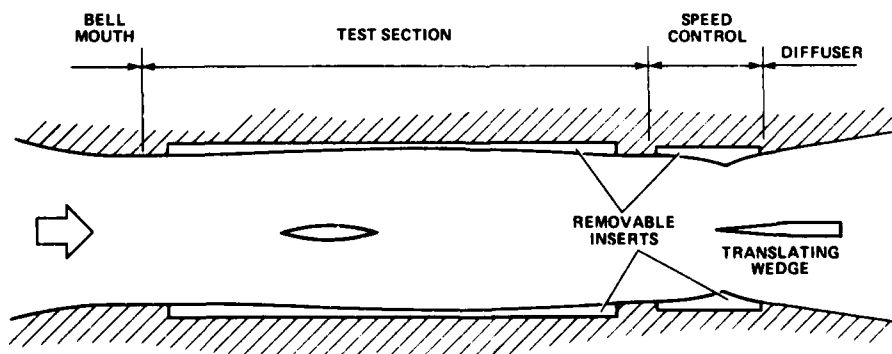


Figure 10 Oscillating flow facility - MARVIN

Flow title: MIZUSHINA (I)

Flow type: Class B, fixed surface, fully developed pipe flow

Participating research personnel: T. Maruyama, T. Mizushina, and Y. Shiozaki

Primary reference: Pulsating Turbulent Flow in a Tube. Mizushina et al., 1973b

Facility:

Location: Department of Chemical Engineering, Kyoto U., Kyoto, Japan

Apparatus: Water tunnel with chemicals added (no diagram available at date of publication)

Test section: Circular tube, 2 cm diameter, 2 m long; tests conducted 150 diameters from inlet

Oscillation mechanism: Two bellows pumps, one at inlet, one at outlet, 180° out of phase

Pressure gradient mechanism: None

Measurement surface: Wall of tube

Trip: None

Wall boundary-layer control: None

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of axisymmetry: Not specified

Measurement accuracy: Not specified

Measurement technique: Electrochemical probe in chemically treated water, recorded on magnetic tape; pressure transducer also recorded

Data-reduction technique: Ensemble average, 20 cycles for velocity on hybrid computer. Pulsating component obtained using high-pass filter

Nominal test conditions: $U_0 = 100$ cm/sec; $U_1 = 32\%$ to 43% ; $Re = 10^4$; $f = 0.12$ to 1.3 Hz; $X_0 = 150$ diameters from inlet

Availability of data:

Graphic data presented in report: Phase-averaged instantaneous profiles at eight phases through cycle:

$\langle u \rangle$, $\langle \tau \rangle$, $\langle -u'v' \rangle$, $\langle \epsilon_m \rangle$, $\langle u' \rangle$ vs y , $Re = 10^4$, $f = 0.126, 0.75$ Hz

Data on magnetic tape: None (availability of digital data not yet established)

Comments by LWC: This experiment presents instantaneous data for periodic motion in a pipe. The authors find that the flow behavior depends on whether the driving frequency is above or below a critical value associated with the bursting frequency of a steady turbulent boundary layer. For low-frequency oscillation, the velocity profiles vary through the cycle, but are still similar to steady-state profiles. However, the turbulence intensity does not vary through the cycle, so the flow is not in full equilibrium. For high frequency, all the measured parameters (u , u' , τ , $-u'v'$) are significantly different from steady flow. The authors suggest that turbulent bursts having the same frequency as the pulsation dominate the flow at frequencies above the critical value. This experiment would be a good test for evaluating turbulence modeling.

Related references: Mizushina, et al., 1973a

Flow title: MIZUSHINA (II)

Flow type: Class B, fixed surface, fully developed pipe flow

Participating research personnel: H. Hirasawa, T. Maruyama, and T. Mizushima

Primary reference: Structure of the Turbulence in Pulsating Flows. Mizushima et al., 1975

Facility:

Location: Department of Chemical Engineering, Kyoto U., Kyoto, Japan

Apparatus: Water tunnel with chemicals added (no diagram available at date of publication)

Test section: 5.16-cm i.d. pipe, measured in 78 diameters from inlet

Oscillation mechanism: Bellow pumps at entrance and exit

Pressure gradient mechanism: None

Measurement surface: Wall of pipe

Trip: None

Wall boundary-layer control: None

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of axisymmetry: Not specified

Measurement accuracy: Not specified

Measurement technique: Electrochemical mass-transfer probe

Data reduction technique: Analog-to-digital conversion and data reduction performed on hybrid computer.
Ensemble average performed at 32 phase angles for 100 cycles of data.

Nominal test conditions: U_0 = not directly specified (estimated at 53 cm/sec; U_1 = 47%, 61%;
 TU_0/D = 6.49, 20.4; f = not directly specified (data all presented for nondimensional parameter TU_0/D)

Availability of data:

Graphic data presented in report:

$\left. \begin{array}{l} \langle u \rangle \text{ vs } y/R \\ \langle u' \rangle / u^* \text{ vs } y/R \end{array} \right\}$ at eight angles through cycle, $Re = 10^4$, $TU_0/D = 6.49$

$\left. \begin{array}{l} \langle u \rangle \text{ vs } y/R \\ \langle u' \rangle / \bar{u} \text{ vs } y/R \end{array} \right\}$ at eight phase angles, $Re = 10^4$, $TU_0/D = 20.4$

Digital data on magnetic tape: None (availability of digital data not yet established)

Comments by LWC: The dynamic process of turbulent bursting in pulsating turbulent flow was studied. The authors find that resonance in pulsating flows only affects the generation of turbulence. In the preferred range of burst period, the turbulence generated near the wall by the flow pulsation propagates toward the centerline with a propagation time that is independent of the pulsation period and scales on the wall parameters

Related references: Mizushima et al., 1973a; Mizushima et al., 1973b

Flow title: OHMI

Flow type: Class B, fixed surface, fully developed pipe flow

Participating research personnel: M. Ohmi, T. Usui, O. Tanaka, and M. Toyama

Primary reference: Pressure and Velocity Distribution in Pulsating Turbulent Pipe Flow. Ohmi et al., 1974

Facility:

Location: Osaka U., Osaka, Japan

Apparatus: (A) Open-return air tunnel; (B) gravity fed water tunnel (see fig. 11)

Test section: (A) Pipe, 50.4-mm o.d., 5-mm wall; (B) pipe, 79-mm o.d., 5-mm wall

Oscillating mechanism: (A) Butterfly valve, 49.7 mm diameter upstream of test section; (B) butterfly valve, 75 mm diameter, downstream of test section

Pressure gradient mechanism: None

Measurement surface: Wall of tube

Trip: Not specified

Wall boundary-layer control: None

Natural frequency: 12 Hz

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Velocities measured using hot-film probe in water, hot-wire probe in air; pressure transducer for pressure measurement both in air and water

Data reduction techniques: Ensemble-averaged data, number of cycles averaged not specified

Nominal test conditions: $U_0 = 45$ m/sec (air), (value not specified for water); $Re = 7,740$ to $95,900$ (air), $47,000$ to $74,100$ (water); $U_1 = 5.3\%$ to 47% (air), (value not specified for water); $f = 0.0432$ to 48 Hz (air), 0.5 to 3.0 Hz (water); $X_0 =$ not specified

Availability of data:

Graphic data presented in report:

(1) Phase-averaged profiles at 12 phase angles through cycle for u_p/u_{pCL} vs r/R , $f = 0.0432$, $Re = 67,500$ (air)

(2) \bar{u}/\bar{u}_{CL} vs r/R for eight cases (air)

(3) Amplitude and phase of oscillating velocity for air at:

f	Re
0.043	67,500
6.0	47,600
48.0	68,300
24.0	7,740
24.0	69,700

(4) Axial distributions of oscillating pressures and centerline velocities for seven cases

Data on magnetic tape: None (status of digital data not determined at time of publication)

Comments by LWC: This study was directed toward documentation of pressure and velocity behavior of pulsating water and air flows as a function of Reynolds number frequency and amplitude. The authors find that the time-averaged velocities agree well with steady flow velocities and that they are able to predict the oscillating velocity profiles accurately; they find dependence only on Reynolds number and a dimensionless angular frequency $\omega' = \omega R^2/\nu$.

Related references: None

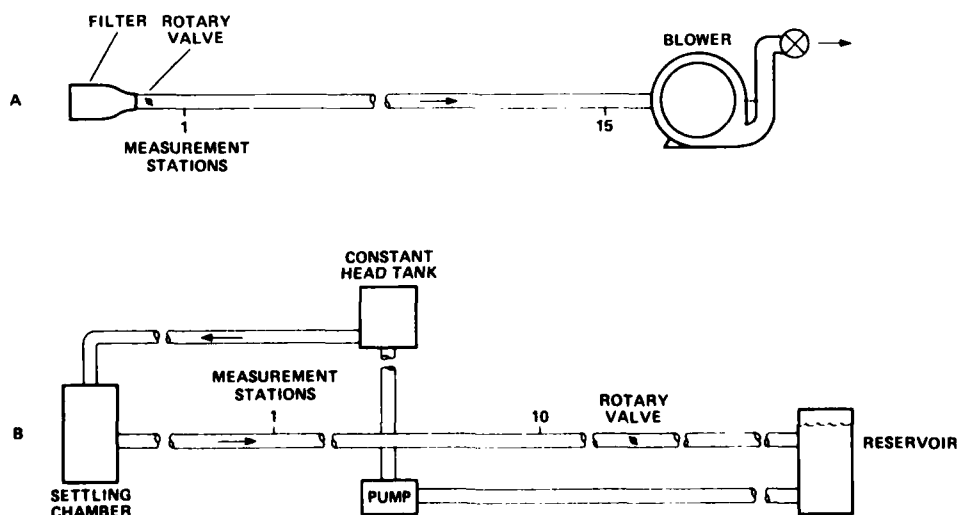


Figure 11 Oscillating flow facility - OHMI

Flow title: OSTROWSKI

Flow type: Class B, fixed flat surface, boundary-layer, impulsive start

Participating research personnel: J. Ostrowski and J. Wojciechowski

Primary reference: The Generation of a Turbulent Boundary Layer in Unsteady Flow. Ostrowski and Wojciechowski, 1977

Facility:

Location: Technological U., Warsaw, Poland

Apparatus: Two-dimensional air duct with perforated upper surface (see Fig. 12)

Test Section: $0.2 \times 0.3 \times 1.4$ m

Oscillation mechanism: Controllable shutters upstream of test section; includes capability for impulsive start

Pressure gradient mechanism: None

Measurement surface: Floor of tunnel

Trip: Roughness elements, 1 cm tall, 1×2 cm at base, checkerboard pattern, 1 m length before test section

Wall boundary-layer control: Porous ceiling of tunnel

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: A combination of six hot-wire probes, recorded at seven x locations on oscillograph paper; pressures recorded 100 mm above floor using pressure transducer

Data-reduction technique: Manual reduction of data from oscillograph traces

Nominal test conditions: U_0 = impulsive start, 0 to 45 m/sec; steady U_0 = 45 m/sec after $t = 0.15$ sec;
 Re = not specified ($\delta = 8$ cm); U_1 = not applicable; f = not applicable; X_0 = approximately 700 mm after roughness ends

Availability of data:

Graphic data Presented in report:

$u(y,t)$ recorded at $x = -1, 0, 0.15, 0.6, 0.9, 1.2$ m

$u/U_0(x,t)$ for impulsive start, 10 time values

p/q_0 , u_{rms}/U_0 , \bar{u}/U_0 vs t

$\langle u \rangle / \langle u_0 \rangle$ vs y for six time values at $x = 0.0, 0.3, 1.2$ m

$\langle u_{rms} \rangle / \langle u_0 \rangle$ vs y for nine time values at $x = 0.0, 0.15, 0.3$ m

Data on magnetic tape: None (no digital data exist)

Comments by LWC: This report describes the development of an unsteady turbulent boundary layer on the lower surface of a two-dimensional duct after passage over a roughness area. The data are presented for an impulsively started flow and are documented until steady-state conditions are attained.

Related references: Wojciechowski, 1976

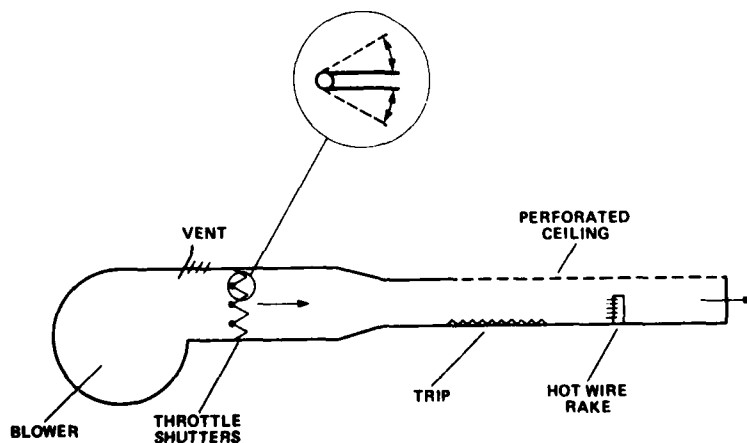


Figure 12 Oscillating flow facility - OSTROWSKI

Flow title: PARIKH

Flow type: Class A, fixed flat surface, adverse pressure gradient, boundary layer

Participating research personnel: R. Jayaraman, P. Parikh, and W. C. Reynolds

Primary reference: On the Behavior of an Unsteady Turbulent Boundary Layer. Parikh et al., 1981(a)

Facility:

Location: Department of Mechanical Engineering, Stanford U., Stanford, Calif.

Apparatus: Open return water tunnel (see Fig. 13)

Test section: 2-m development section followed by 0.6-m test section, 0.3 m wide

Oscillation mechanism: A unique system using variable strength suction through holes opposite the test section and recovery section surfaces

Pressure gradient mechanism: Suction strength varies sinusoidally in such a way as to produce a variable strength adverse pressure gradient on the test surface while maintaining constant inflow at the entrance to the test section

Measurement surface: Top wall of tunnel development section and test section

Trip: Metal plate (0.0625 in. high, 0.500 in. long) mounted spanwise at entrance to development section

Wall boundary-layer control: (1) The nozzle boundary layer on the top wall at the entrance to the development section is removed through a slot; (2) the sidewall boundary layers are removed by slots located at the start of the test section; (3) uniform free-stream velocity in the development section is ensured by boundary-layer suction at discrete stations along lower wall of tunnel

Natural frequency: 29 Hz

Maximum wall deflection: 0.001 in. at resonance (estimated)

Positional accuracy: 0.001 in.

Free-stream turbulence: 0.3-0.5%

Verification of two-dimensionality: Measured spanwise variation of momentum thickness at three lateral stations across the entrance to the test section were within 6%

Measurement accuracy: Not specified

Measurement technique: Pitot-static tube; one-channel forward-scatter laser anemometer using a Bragg cell

Data-reduction technique: For the low-amplitude preliminary study, the periodic component of velocity has been extracted using cross-correlation with the pulser signal. Digital ensemble-averaging is currently being performed on-line to obtain $\langle u \rangle$, $\langle u'_{rms} \rangle$

Nominal test conditions (at entrance to test section): $U_{\infty,0} = 0.73$ m/sec; $X_0 = 2.0$ m; $\delta_0 = 0.05$ m;

$0 \leq f \leq 2$ Hz; $U_{\infty}(x,t) = U_{\infty,0} - a_0(x - X_0)/L(1 - \cos \omega t)$

Authors define: $\alpha = a_0/U_{\infty,0}$; $0 \leq \alpha \leq 0.2$; $\beta_\delta = f\delta/U_{\infty,0}$; $0 \leq \beta_\delta \leq 0.14$

Availability of data:

Graphic data presented in report (all measurements at $x - X_0 = 0.568$ m):

$\alpha = 0.05$; $U_{\infty,0} = 0.73$ m/sec

\bar{u} vs y , $f = 0, 0.5, 2.0$ Hz; $\phi_0 = 0^\circ, 90^\circ, 180^\circ$

$\sqrt{u'^2}/\bar{u}_e$ vs y , $f = 0, 0.25, 0.5, 2.0$ Hz

$|u_p|/|u_{pe}|$ vs y , $f = 0, 0.25, 0.5, 2.0$ Hz

$\phi(u)$ vs y , $f = 0, 0.25, 0.5, 2.0$ Hz

$\langle \delta \rangle / \bar{\delta}$ vs ϕ_0 , $f = 0, 0.25, 0.5, 2.0$ Hz, $(\langle C_f \rangle - \bar{C}_f) / \bar{C}_f$ vs ϕ_0 , $f = 0.0, 0.25, 0.5, 2.0$ Hz

Data on magnetic tape (data supplied by authors): Digital data for all data in report (Parikh, Reynolds, and Jayaraman) is on magnetic tape

Comments by LWC: This is the first data to come from this unique facility. The flow develops as a steady flat-plate flow during passage through the development section, and then enters the test section where the flow oscillates between zero-pressure gradient and a pressure gradient associated with a linearly decreasing free-stream velocity. Based on this low-amplitude data, the authors find that the mean-velocity profile is independent of frequency or amplitude effects. The periodic component shows a greater variation as the frequency changes. The amplitude of fluctuation within the boundary layer decreases with increase of frequency. The phase of the boundary-layer periodic component shows a lead very near the wall, with a lag in the outer regions of the layer. These preliminary data are included in order to make these results more readily available. The experimenters plan to test high-amplitude cases, and to document fully the results. At that time, the pertinent data will be added to the digital data library.

Related references: Parikh et al., 1981(b)

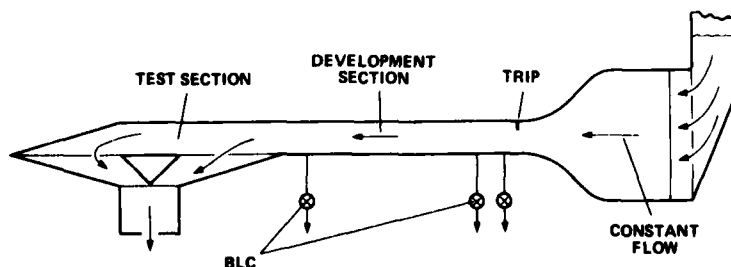


Figure 13 Oscillating flow facility - PARIKH

Flow title: PATEL

Flow type: Class A, fixed flat surface, time-dependent traveling-wave, boundary layer

Research personnel involved: M. H. Patel

Primary reference: On Turbulent Boundary Layers in Oscillatory Flow. Patel, 1977

Facility:

Location: Queen Mary College, Mile End Road, U. of London, London, England

Apparatus: Open-return blow-down wind tunnel (see Fig. 14)

Test section: Semiopen (open top and bottom; closed sides); cross section; 0.76 m high, 0.99 m wide, 2 m long

Oscillation mechanism: Upper and lower surfaces of nozzle exit are flexible flaps; when deflected simultaneously these induce a traveling vortex pattern which then moves down the tunnel

Pressure gradient mechanism: No mean pressure gradient

Measurement surface: Upper surface of splitter plate placed horizontally in the center of the plane jet (0.9 m wide by 2.0 m long)

Trip: Sandpaper located 27.5 cm aft of leading edge

Wall boundary-layer control: Not specified

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: Not specified

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Simultaneous measurements of velocity in boundary layer and free-stream flow using hot-wire anemometers

Data-reduction technique: Magnitude and phase of oscillatory velocity obtained by digital signal processing. Longitudinal turbulence intensity obtained using analog rms meter

Nominal test conditions: $U_0 = 19.8$ m/sec; $Re_0 = 2000$ to 4000 ; $U_1 = 3$ to 8% ; $f = 4$ to 12 Hz; $X_0 = 0.6$ to 1.8 m;
 $u(x,t) = U_0(1 + U_1 e^{i\omega(t-x/c)})$

Availability of data:

Graphic data presented in report:

(1) θ, R_θ, H vs x for steady flow, $x = 0.6$ to 1.8 m

(2) \bar{u}/\bar{u}_e vs y , $x = 1.288$ m; $f = 0, 6, 10$ Hz, $U_1 = 3\%$

(3) amplitude and phase profiles of fluctuating velocity for

$x = 1.288$ m, $U_1 = 3\%$, $f = 4, 6, 8, 10, 12$ Hz;

$x = 1.288$ m, $f = 8$ Hz, $U_1 = 2, 3, 5, 7, 8\%$

$x = 1.516$ m; $U_1 = 4\%$, $f = 4, 5, 6, 7, 8, 9, 10, 11, 12$ Hz

(4) longitudinal turbulence intensity profiles, $x = 1.516$, $U_1 = 4\%$; $f = 0, 4, 5, 6$ Hz

Data on magnetic tape (digital data supplied by author): Mean velocity; amplitude of in-phase and out-of-phase velocity components; amplitude and phase of boundary layer velocity compared to free stream; each vs y for:

$x = 1.28$ m, $U_1 = 4.23\%$; $f = 4, 6, 8, 10, 12$ Hz

$x = 1.516$ m, $U_1 = 5.7\%$; $f = 4, 5, 6, 7, 8, 9, 10, 11, 12$ Hz

$x = 1.745$ m, $U_1 = 5.6\%$; $f = 4, 6, 8, 10, 12$ Hz

Comments by LWC: This facility uses the vortices shed from oscillating flaps at the exit of the entrance nozzle to induce traveling unsteady pressure gradient effects on the surface of the splitter plate. Patel notes that the mean flow and turbulence intensity distributions are insensitive to the free-stream oscillations tested, but that phase lag levels across the boundary layer increase with free-stream amplitude greater than 5% .

Related references: Patel, 1975; Kenison, 1977a, 1977b; Pericleous, 1977

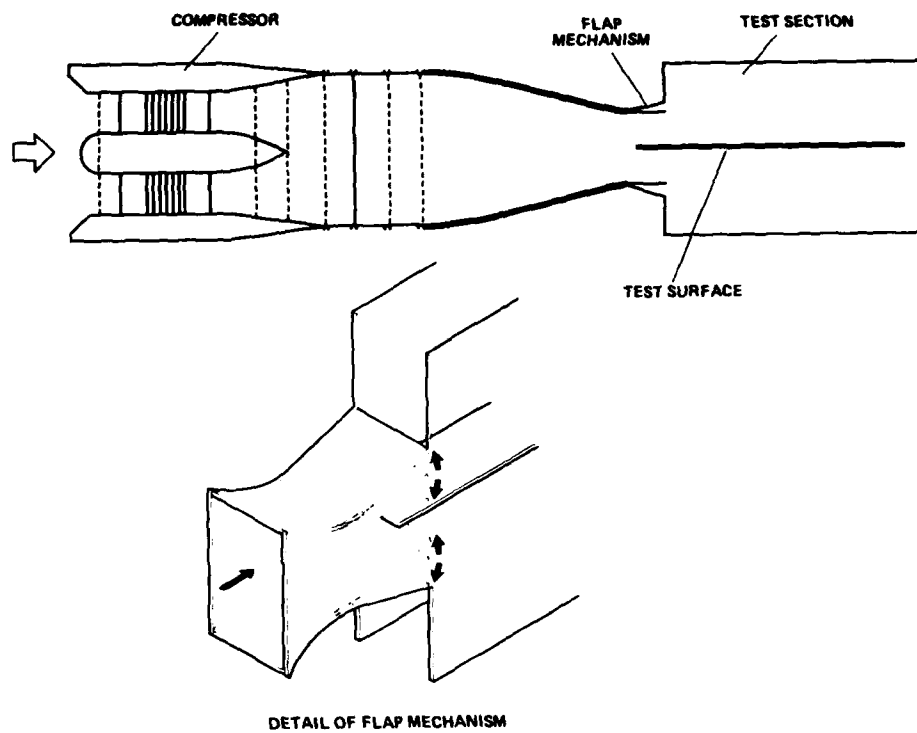


Figure 14 Oscillating flow facility - PATEL

Flow title: PERICLEOUS

Flow type: Class B, fixed curved surface, time-dependent traveling wave plus mean adverse pressure gradient, boundary layer

Participating research personnel: K. A. Pericleous

Primary reference: An Oscillatory Turbulent Boundary Layer in an Adverse Pressure Gradient. Pericleous, 1977

Facility:

Location: Queen Mary College, Mile End Road, U. of London, London, England

Apparatus: Open-return blow-down wind tunnel

Test section: Semiopen (open top and bottom; closed sides) (see Fig. 15)

Oscillation mechanism: Upper and lower surfaces of nozzle exit are flexible flaps; when deflected simultaneously they induce a traveling vortex pattern which then moves down the tunnel

Pressure-gradient mechanism: An "S" shaped airfoil imposing a favorable, then adverse pressure gradient on the measuring surface; chord = 2 m; thickness ratio = 3.6% (see Fig. 15)

Measurement surface: Top surface of airfoil installed in test section

Trip: No trip applied; natural transition occurred at $x/c = 0.23$

Natural frequency: Not specified

Maximum wall deflection: Not specified but author indicates some difficulty was encountered

Positional accuracy: 0.001/ft for traverse

Free-stream turbulence: 0.2%-0.5% depending on x for steady flow; author reports values of 2% to 3.4% for unsteady cases, but cautions that these numbers may be erroneous

Verification of two-dimensionality: Tufts were placed on tunnel walls and on both surfaces of model.

No separation was observed on measurement surface; separation on lower surface only after $x/c = 0.945$; separation line was not dependent on span

Measurement accuracy: Not specified

Measurement technique: Pressure transducers were connected to the model through pressure tubing for pressure measurement. Two hot-wire anemometers were used for velocity measurements: one mounted on a traversing mechanism fixed on the model surface, and the other installed on a three-degree-of-freedom, free-stream survey apparatus.

Data-reduction technique: The time-mean value, \bar{u} , was obtained by 8-sec averages on a digital voltmeter. The turbulence rms value was obtained by using either an rms meter, or by a time-domain analyzer. The amplitude and phase information were obtained using Fourier summation, with a maximum of eight repetitions of the event being studied

Nominal test conditions: $U_0 = 21.9$ m/sec, flap amplitude = 4 in.; $f = 1$ to 6 Hz; $U_1 = 0$ to 10%;
 $u_e = U_0(1 + U_1 e^{i\omega(t-x/c)})$

Availability of data:

Graphic data presented in report: Velocity and pressure distribution data, and documentation of facility performance; rms amplitudes of u and p vs f for eight x/c

Steady data: \bar{u}/U_0 , u'/U_0 vs y , $x/c = 0.378, 0.507, 0.566, 0.614, 0.732, 0.782$

Unsteady data:

$u_p(A, \phi)$ vs y ; $f = 2, 3, 4, 5, 6$; $x/c = 0.378, 0.507, 0.566, 0.614, 0.684, 0.732, 0.782$

u'/U_1 vs y ; $f = 2, 3, 4, 5, 6$; $x/c = 0.567, 0.614, 0.684$

Data on magnetic tape: None (digital data no longer exist)

Comments by LWC: This experiment is part of a series performed at the University of London (Patel, Kenison). Although limited to one amplitude and frequency, this combination of spatial and temporal pressure gradients offers an interesting study case, since both steady and unsteady measurements are presented for the same test conditions. Note that the data are the result of Fourier analysis, and therefore neglect any higher-order harmonic content of the original signal.

Related references: Patel, 1975, 1977; Kenison, 1977a, 1977b

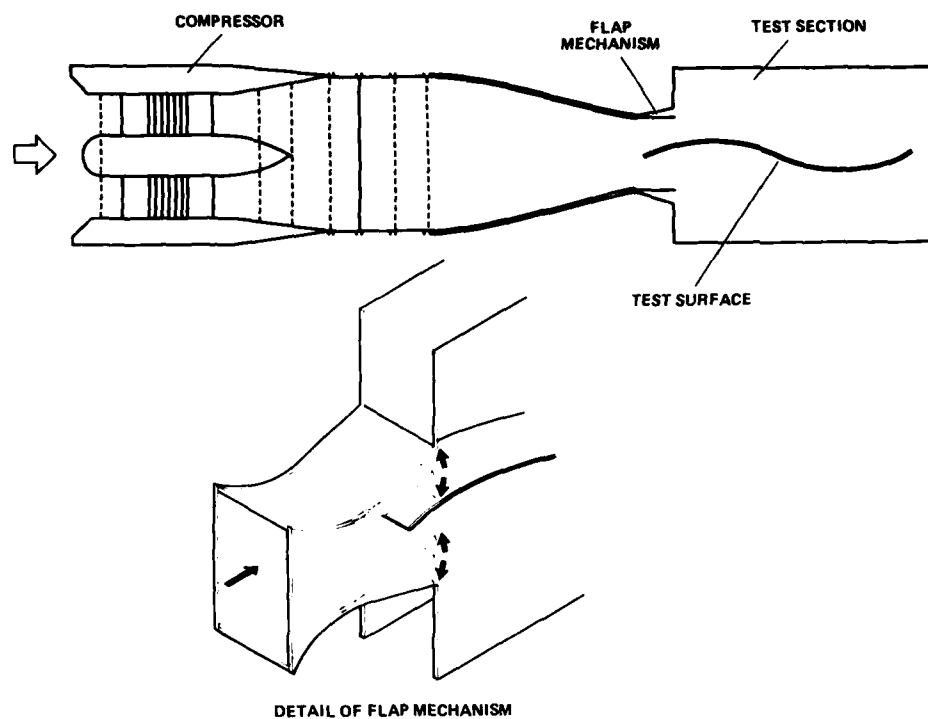


Figure 15 Oscillating flow facility — PERICLEOUS

Flow title: RAMAPRIAN

Flow type: Class A, fixed surface, fully developed pipe flow

Participating research personnel: B. R. Ramaprian and S. W. Tu

Primary reference: Experiments on Transitional Oscillatory Pipe Flow. Ramaprian and Tu, 1979

Facility:

Location: Iowa Institute of Hydraulic Research, Iowa City, Iowa

Apparatus: Continuous gravity feed oil tunnel (see Fig. 16)

Test section: 300 mm long, 50-mm i.d. pipe; 8.8-m development pipe

Oscillation mechanism: Rotating sleeve at end of pipe, profiled to produce sinusoidal flow in pipe

Pressure gradient mechanism: None

Measurement surface: Inner wall of pipe

Trip: None

Wall boundary-layer control: None

Natural frequency: Not specified

Maximum wall deflection: Not specified

Positional accuracy: 1 mm

Free-stream turbulence: Not specified

Verification of axisymmetry: Not specified

Measurement accuracy: Not specified

Measurement technique: Laser doppler anemometer with frequency shifter for velocity measurement

Data-reduction technique: Computer-controlled data acquisition system ensemble-averaged signals, 48 samples per cycle, 300 cycle average

Nominal test conditions: $U_0 = 0.574$ m/sec; $f_t = 2.3$ Hz; $u_* = 0.0535$ m/sec; $U_1 = 15\%$; $Re_D = 2100$ (mean); $f = 1.75$ Hz

Availability of data:

Graphic data presented in report: All data for $f = 1.75$ Hz, fully turbulent flow (unsteady laminar and transitional data in report are not reviewed here) u_p vs ϕ_0 , three radial stations u_p vs η for eight ϕ_0 positions $\sqrt{u_p'^2}$ vs η for eight ϕ_0 positions $\sqrt{u_p'^2}$ vs ϕ_0 for three radial stations $\langle u \rangle$ vs η for seven ϕ_0 positions $\langle u'v' \rangle$ vs ϕ_0 for three radial stations \bar{u}/\bar{u}_{max} vs η , steady at U_{max} ; unsteadyData on magnetic tape (supplied by authors): Quasi-steady average velocity values at 30° phase increments through cycle, $\langle u \rangle$, $\sqrt{u_p'^2}$ vs y , at 30° increments through cycle

Comments by LWC: This experiment studied laminar, transitional and fully turbulent oscillatory pipe flow (only the turbulent flow is presented here). The authors conclude that the fully turbulent mean and periodic structure qualitatively resemble the laminar counterparts. When the oscillation frequency is of the same order as the characteristic frequency of the turbulence, significant interactions occur. The time-mean velocity profile exhibits an inflection point near the wall, and the periodic velocity component has a larger overshoot in the Stokes layer than a corresponding laminar flow. The ensemble-averaged turbulence intensity is frozen everywhere in the pipe during oscillation at the interactions frequency. The ensemble-averaged Reynolds stress is also frozen at an average value except very near the wall.

Related references: Ramaprian and Tu, 1981

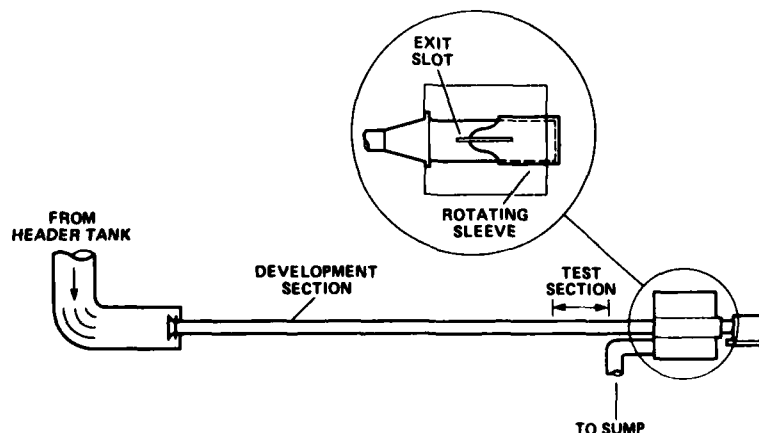


Figure 16 Oscillating flow facility - RAMAPRIAN

Flow title: SAXENA

Flow type: Class B, fixed airfoil, adverse pressure gradient, boundary layer

Participating research personnel: L. S. Saxena

Primary reference: An Experimental Investigation of Oscillating Flows Over an Airfoil. Saxena, 1977

Facility:

Location: Illinois Inst. of Tech., Chicago, Ill.

Apparatus: Closed-circuit oscillating-flow wind tunnel (see Fig. 17)

Test section: $2 \times 2 \times 6$ ft

Oscillation mechanism: Four rotating vanes at downstream end of test section

Pressure gradient mechanism: 8-in. and 12-in.-chord NACA 0012 airfoils

Measurement surface: NACA 0012 airfoil

Trip: Beads of glue, 1.5 mm high, 2.5 mm diameter, bonded 5 mm apart to a strip of masking tape, starting at the leading edge

Wall boundary-layer control: Not specified

Natural frequency: 10.0 Hz

Maximum wall deflection: Not specified

Positional accuracy: Hot-wire probe, 0.1 mm; angle of airfoil, 0.2°

Free-stream turbulence: Not specified

Verification of two-dimensionality: Not specified

Measurement accuracy: Not specified

Measurement technique: Seven surface hot-film gages; 18 pressure taps on upper surface connected to Scani-valve and dynamic pressure transducer; constant temperature hot wire above surface and in wake moved by traversing carriage; probe position determined by measuring the distance between the hot-wire element and its reflection from the airfoil surface; free-stream reference located 15 in. upstream, and 8 in. above leading edge with airfoil at zero degrees; no tunnel corrections applied

Data-reduction technique: Analog waveform reduction, 100 segments per cycle, 100 cycles per data point

Nominal test conditions: Low frequency: 12-in.-chord airfoil; $\alpha = 11^\circ$; $f = 2.22$ Hz; $U_0 = 38$ ft/sec;

$U_1 = 19\%$; $Re = 2.5 \times 10^5$. High frequency: 8-in.-chord airfoil; $\alpha = 10^\circ$, $f = 10.8$ Hz;

$U_\infty = 38$ ft/sec; $U_1 = 19\%$; $Re = 1.7 \times 10^5$

Availability of data:

Graphic data presented in report:

Steady data: \bar{u}/U_0 , u'_{rms}/U_0 vs y ; $U_0 = 38$ ft/sec; 8 in. chord, $x/c = 0.95$; $\alpha = 0, 5, 7.5, 8.2, 9, 10.5^\circ$

\bar{u}/U_0 , u'_{rms}/U_0 vs y ; $U_0 = 38$ ft/sec; 8 in. chord; $\alpha = 8.2^\circ$; $x = 0.71, 1.5, 2, 2.5, 19$ mm

\bar{u}/U_0 , u'_{rms}/U_0 vs y ; $U_0 = 38$ ft/sec; 12 in. chord; $\alpha = 11^\circ$; $x/c = 0.062, 0.072, 0.106, 0.506, 0.756$

$C_p(x)$, $U_0 = 38$ ft/sec; $\alpha = 0, 6, 9, 11, 14.2^\circ$

Unsteady data: $C_p(x)$; $f = 2.22$; $\alpha = 11^\circ$; $\partial u/\partial t = 0$, $u = u_{min}$; $\partial u/\partial t > 0$; $\partial u/\partial t = 0$, u_{max} ; $\partial u/\partial t < 0$

$C_p(x)$, $f = 2.22$; $\alpha = 11$; $\partial u/\partial t = 0$, u_{min} ; $\partial u/\partial t > 0$; $\partial u/\partial t = 0$, u_{max} ; $\partial u/\partial t < 0$

$C_p(x)$, $\alpha = 14.2$; $f = 2.22$, four (t/T)

$C_p(x)$, $f = 9.66$; $\alpha = 11$; $\partial u/\partial t = 0$, u_{min} ; $\partial u/\partial t > 0$; $\partial u/\partial t = 0$, u_{max} ; $\partial u/\partial t < 0$

$C_p(x)$, $\alpha = 14.2$, $f = 9.66$; four (t/T)

u/U_0 vs y , 12-in. airfoil, no trip, $\alpha = 11^\circ$; $f = 2.22$, four (t/T); $x/c = 0.031, 0.046, 0.062, 0.075, 0.106, 0.263, 0.506, 0.756, 0.92$

u/U_0 vs y , 12-in. airfoil with trip, $\alpha = 11^\circ$, $f = 2.22$, four (t/T); $x/c = 0.062, 0.106, 0.506, 0.756$

u/U_0 vs y , 12-in. airfoil with trip, $\alpha = 11^\circ$, $f = 9.66$, four (t/T); $x/c = 0.062, 0.106, 0.506, 0.756$

u/U_0 vs y , 8-in. airfoil, no trip, $\alpha = 10^\circ$, $f = 10.8$, four (t/T); $x/c = 0.756, 0.92$

u/U_0 vs y , 8-in. airfoil, no trip, $\alpha = 10^\circ$, $f = 10.8$, four (t/T); $x/c = 0.025, 0.045, 0.07, 0.095, 0.15, 0.50, 1.04$

u/U_0 vs y , 8-in. airfoil, no trip, $\alpha = 15^\circ$, $f = 10.8$, four (t/T); $x/c = 0.025, 0.05, 0.15, 0.50, 0.75, 1.05$

Data on magnetic tape: None (no digital data exist)

Comments by LWC: This experiment documents the flow over a fixed airfoil in a pulsating free stream. Quasi-steady airfoil behavior was observed by the original author for angles below a critical value. However, when α -critical was exceeded for the high-frequency case, the quasi-steady behavior disappeared, and large periodic excursions from the mean lift were observed.

Related references: Saxena, Fejer, and Morkovin, 1977

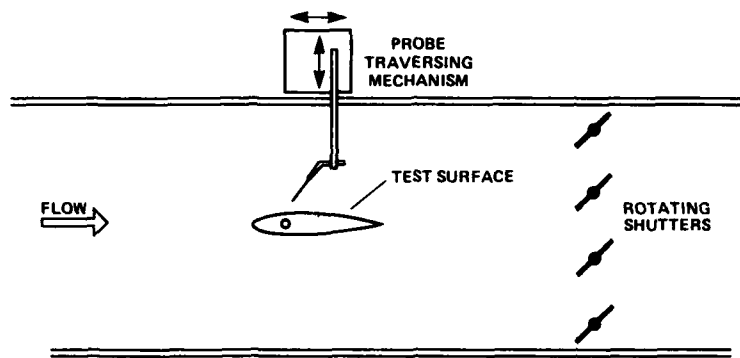


Figure 17 Oscillating flow facility - SAXENA

Flow title: SCHACHENMANN

Flow type: Class B, fixed axisymmetric diffuser, adverse pressure gradient, boundary layer

Participating research personnel: D. Rockwell and A. Schachenmann

Primary reference: Oscillating Turbulent Flow in a Conical Diffuser. Schachenmann, 1974

Facility:

Location: Department of Mechanical Engineering, Lehigh U., Bethlehem, Pa.

Apparatus: Open-return wind tunnel (see Fig. 18)

Test section: Conical diffuser inlet diameter 102 mm, length 609 mm, half angle 3°

Oscillation mechanism: Sliding-plate wave-maker valve located 258 mm upstream of inlet

Pressure gradient mechanism: Conical diffuser

Measurement surface: Wall of diffuser

Trip: None; a constant diameter duct 114 cm long before the diffuser allowed natural transition

Wall boundary-layer control: None

Natural frequency: Not specified

Maximum dynamic wall deflection: Not specified

Positional accuracy: x direction, 0.001 in.; y-direction, ± 0.005 in.

Free-stream turbulence: 2%

Verification of two-dimensionality (replaced by verification of axisymmetry since flow is in diffuser):

Velocity measurements across cross section show identical results

Measurement accuracy: Not specified

Measurement techniques: A hot-wire anemometer was mounted on a traversing carriage located at the exit of the nozzle, permitting horizontal and vertical movement; steady static pressures were measured along the core of the diffuser by pitot-static tube. The oscillatory velocity measurements were made using a hot-wire anemometer; the oscillatory pressure measurements were made using a "microphone" pressure transducer mounted on the wall of the diffuser.

Data reduction techniques: The hot-wire signal was averaged, then fed to a damped dc voltmeter for time mean values; an rms voltmeter obtained the rms value of the total velocity fluctuations. The hot-wire signal was also sent to an A/D converter, and ensemble-averages were performed on a computer. The pressure signals were processed using the same approach.

Nominal test conditions: Inlet $U_0 = 60.0, 100.0$ fps; $U_1 = 1$ to 10%; $\delta^*/R = 0.012$; $\theta/R = 0.01$; $10^4 < Re < 5 \times 10^6$; $S = 1.0, 7.33$

Availability of data:

Graphic data presented in report:

Steady data:

\bar{u}/\bar{u}_{CL} ; u_{rms}/\bar{u} vs y at $x/L = 0, 0.25, 0.5, 0.75, 1$; $U_0 = 60.0, 100.0$ fps

\bar{u}/U_0 , $\Delta p/q_0$, u_{rms}/U_0 vs x/L , $U_0 = 60.0, 100.0$ fps

Unsteady data:

\bar{u}/\bar{u}_{CL} , u_{rms}/\bar{u}_{CL} , $A(u_p/u_{pCL})$, $\phi(u_p/u_{pCL})$ vs y/R for:

$U_0 = 60$ fps; $U_1 = 1.3, 1.8, 2.0, 2.8, 8.3, 9.5\%$; $x/L = 0.0, 0.25, 0.5, 0.75, 1.0$

$U_0 = 100$ fps; $U_1 = 2.0, 2.5, 4.3, 4.8, 6.9\%$; $x/L = 0.0, 0.25, 0.5, 0.75, 1.0$

Data on magnetic tape: None (digital data no longer exist); see TOMSHO for further details

Comments by LWC: This experiment was primarily directed toward understanding the potential flow behavior of oscillating diffuser flow. However, the boundary-layer behavior plays a significant part in the flow development and the results of the study offer insight into this viscous behavior. The author found that the amplitude of the organized velocity fluctuations can exceed the core flow amplitude by as much as an order of magnitude. At low frequency, the phase of these fluctuations leads the local core flow fluctuation but at higher frequencies the velocity fluctuations can lag the free stream, extending most of the way across the boundary layer. In either case, the mean flow field of the diffuser remains essentially unchanged from the steady flow behavior.

Related references: Schachenmann and Rockwell, 1976; Tomsho, 1978

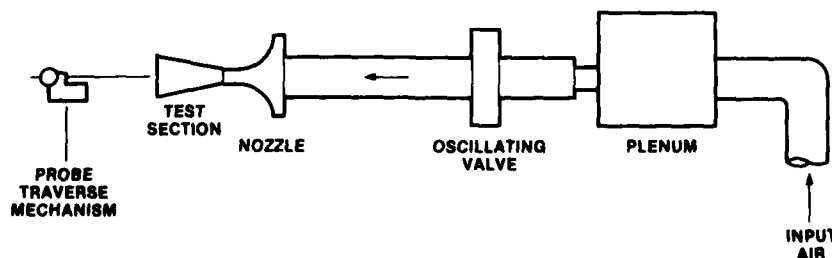


Figure 18 Oscillating flow facility - SCHACHENMANN

Flow title: SIMPSON

Flow type: Class A, fixed flat surface, adverse pressure gradient, boundary layer

Participating research personnel: Y. T. Chew, B. G. Shivaprasad, and R. L. Simpson

Primary reference: Measurements of Unsteady Turbulent Boundary Layers with Pressure Gradients. Simpson et al., 1980

Facility:

Location: Department of Civil and Mechanical Engineering, Southern Methodist U., Dallas, Tex.

Apparatus: Continuous open-circuit wind tunnel (see Fig. 19)

Test section: 8 m long, 0.91 m wide, adjustable upper wall

Oscillation mechanism: Programmable-rotating-blade damper capable of producing nearly single-harmonic sinusoidal waveforms without tunnel resonance

Pressure-gradient mechanism: The test section ceiling forms a convergent-divergent-convergent cross section, thus creating a varying pressure gradient along the test section floor

Measurement surface: The floor of the test section, which is vertically separated from the end of the tunnel contraction by 0.63 cm

Trip: The flow is tripped by the blunt leading-edge of the plywood measuring surface (test section floor)

Wall boundary-layer control: Combinations of active wall suction and blowing slots on all nontest walls at 2.54 m and at 5.08 m; a blowing slot only on these walls at the entrance to the test section

Natural frequency: Not measured, but estimated to be of the order of 10 Hz (sinusoidal oscillation attained without natural frequency contribution)

Maximum wall deflection: 0.002 in.

Positional accuracy: ± 0.002 in. (probe supported from ceiling)

Free-stream turbulence: 1% independent of x

Verification of two-dimensionality: Measured velocity profiles in lateral direction agree within 1%; significant 3D not present until $x > 4.4$ mMeasurement accuracy: Normal hot-wire: $u \pm 2.4\%$, $u'^2 \pm 7\%$; cross hot-wire (including misalignment uncertainty): $u \pm 3.2\%$, $u'^2 \pm 10\%$, $v'^2 \pm 11\%$, $-u'v'$, $\pm 17\%$; laser anemometer: $u, v \pm 0.2$ fps; u'^2 and v'^2 , $\pm 4\%$ maximum profile value; $u'v'$, $\pm 16\%$ maximum profile value; skin friction coefficient: C_f , surface hot-wire, $\pm 12\%$

Measurement techniques: Conventional-wire, x-wire and surface-hot-wire anemometer probes are used. Measurements are made to within 0.05 mm of wall. A two-sensor hot-film unit was used for near-wall measurements. A two-channel directionally sensitive fringe-type laser is used to measure in the region of partially reversed flow. The laser system produces an analog signal based on 400 new signals per second.

Data-reduction technique: A correlator is used to obtain u and v components of the x-wire signal. The data are processed using a minicomputer acting in real-time acquisition mode to obtain ensemble average of velocities and turbulent fluctuations. Ensemble averages take 200 cycles, with 96 samples per cycle

Nominal test conditions: Two flows: Length of converging section = $L = 4.9$ m(1) $U_0 = 16.4$ m/sec, $Re_L = 5.1 \times 10^6$, $\omega L/2U_0 = 0.55$; $f = 0.596$ Hz, $U_1 = 33\%$ (2) $U_0 = 9.1$ m/sec, $Re_L = 2.9 \times 10^6$, $\omega L/2U_0 = 1.0$; $f = 0.596$ Hz, $U_1 = 33\%$

Availability of data:

Graphic data presented in report:

 $\langle u/u_e \rangle$ vs (t/T) for five y positions at $x = 44.75, 112.25, 120, 127, 144, 156$, and 170 in. from X_0 (reference station)Phase angle of first harmonic; amplitudes of first and second harmonics vs $\log y$, for each x station $\langle u/u_e \rangle$ vs $\log y$ at six (t/T) for each x stationPhase angles of first harmonics of $u, u'^2, v'^2, -u'v'$ vs $\log y$ at $x = 31, 44, 52, 64, 74, 87, 105, 108, 112, 121, 127, 138, 144, 156$, and 171 inches

Data presented on magnetic tape (supplied by authors): N.B.: Certain notation is defined by original

authors; e.g., $umrms = \sqrt{\sum \hat{u}^2/n}$; $uprms = \sqrt{\hat{u}^2}$

Flow 1:

LDV data: \bar{u} , $umrms$, $\langle u \rangle$, $uprms$ vs y , $x = 87.56, 106.31$ in. \bar{v} , $vmrms$, $\langle v \rangle$, $vprms$ vs y , seven x locations from 112.375 in. to 170.875 in.Hot-wire data: \bar{u} , $umrms$, $\langle u \rangle$, $uprms$ vs y , ten x locations from 10.875 in. to 112.25 in.X-wire data: \bar{v} , $vmrms$, $\langle v \rangle$, $vprms$, $(-u'v')$, $(-u'v')$ vs y , twelve x locations from 31.375 in. to 144.25 in.Skin friction: $(d\bar{u}/dy)_w$, $dudymrms$, $\bar{\tau}_w/\rho\bar{u}_\infty^2(x)$, $\langle (du/dy)_w \rangle$, $dudyprms$ for thirteen x locationsFree-stream: \bar{u} , $umrms$, $\langle u \rangle$, $uprms$; full x distributionFlow-reversal: streamwise distribution of mean and phase averaged values of near-wall upstream-downstream intermittency; seven x locations

Flow 2:

Hot-wire data: \bar{u} , $umrms$, $\langle u \rangle$, $uprms$ vs y ; six x locations from 32.5 in. to 87.0 in.Skin-friction: $(d\bar{u}/dy)_w$, $dudymrms$, $\bar{\tau}_w/\rho\bar{u}_\infty^2(x)$, $\langle (du/dy)_w \rangle$, $dudyprms$ for thirteen x locationsFree-stream: \bar{u} , $umrms$, $\langle u \rangle$, $uprms$; full x distribution

Comments by LWC: This experiment was performed in a facility that already has been well documented for steady flow (Simpson et al., 1977). This offers an excellent chance to compare predictions of flow in a steady and then unsteady environment.

Related references: Simpson, 1977; Simpson, et al, 1978, 1980, 1981

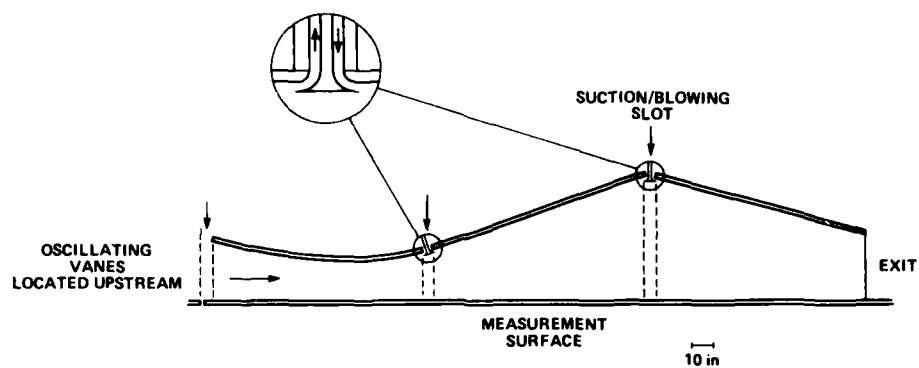


Figure 19 Oscillating flow facility - SIMPSON

Flow title: TOMSHO

Flow type: Class B, fixed axisymmetric diffuser, adverse pressure gradient, boundary layer

Participating research personnel: F. Brown and M. Tomsho

Primary reference: The Oscillating Turbulent Boundary Layer in a Conical Diffuser. Tomsho, 1978

Facility:

Location: Department of Mechanical Engineering and Mechanics, Lehigh U., Bethlehem, Pa.

Apparatus: Open return wind tunnel (see Fig. 18)

Test section: Conical diffuser, inlet diameter 102 mm, length 609 mm, half angle 3°

Oscillation mechanism: Sliding plate, wave-maker valve located 2585 mm upstream of inlet

Pressure gradient mechanism: Conical diffuser

Measurement surface: Wall of diffuser

Trip: None (constant-diameter duct ahead of X_0 permitted natural transition to occur)

Wall boundary-layer control: None

Natural frequency: 110 Hz fundamental; higher harmonics less than 5%

Maximum wall deflection: Not specified

Positional accuracy: y-distance uncertainty, ± 0.125 mm; x-distance uncertainty, 0.001 in.

Free-stream turbulence: 1% at centerline

Verification of two-dimensionality (replaced by verification of axisymmetry for diffuser flow):

Measured values of \bar{u} over whole cross section show identical results

Measurement accuracy: Not specified

Measurement technique: A hot-wire anemometer on a traversing carriage located at the exit of the nozzle permitting horizontal and vertical movement

Data reduction technique: Ensemble average for 500 cycles; amplitude and phase data for velocity

Nominal test conditions: $U_0 = 18.3, 30.5$ m/sec; $Re_D = 150,000$; $\beta = (\delta^*/\tau_w)(dp/dx) = 0.14$ to 17.07 ; $U_1 = 2$ to 10% ; $f = 5$ to 30 Hz; $\omega_x = 2\pi f x / u_{CL}(x) = 0.09$ to 11.7

Availability of data:

Graphic data presented in report:

Steady data:

 $C_p, u_{CL}, du_{CL}/dx$ vs $x, U_0 = 18.3, 30.5$ m/sec; $f = 0$ u/u_{CL} vs y at 13 x stations, $U_0 = 18.3, 30.5$ m/sec; $f = 0$ τ_w, δ^*, H, C_F vs $x, U_0 = 18.3, 30.5$ m/sec; $f = 0$ u^+ vs $y^+, f = 0, U_0 = 18.3$ m/sec $(u - u_{CL})/u^*$ vs $(y/\delta), f = 0, U_0 = 18.3$ m/sec

Unsteady data:

 $A(u)/A(u_{CL}), \phi$ vs $(y/\delta), 13$ x stations, $Re = 113,000$ to $117,000, U_0 = 18.3$ m/sec $A(u)/A(u_{CL}) - 0.047$ to $0.057, f = 5, 10, 15, 20, 25, 30$ Hz $A(u)/A(u_{CL0}), \phi$ vs $x, f = 5, 10, 15, 20, 25, 30$ Hz, $U_0 = 18.3$ m/sec $\langle u \rangle$ vs $(t/T), y/\delta = 0.1, 0.2, 0.4, 0.6, 0.8, 1.0$, centerline; $f = 20$, for two x stations

Data on magnetic tape: None; digital data to be added at later date

Comments by LWC: This experiment follows Schachenmann (1974) and documents the boundary-layer behavior in an oscillating diffuser to complement the study done by Schachenmann with a parametric study for a wide frequency range. This experiment will be valuable for study of both unsteady boundary layer, and potential flow interaction. The author concludes that the oscillation in this conical diffuser results in regions where amplification as well as attenuation can occur. Both phase lead and lag were observed in the outer region whereas phase lead is present in the inner region at all times. The behavior is primarily responsive to the fundamental waveform; the core response pattern is of the same shape as that in the boundary layer but is 180° out of phase. The author states that for the conditions studied, oscillation has no detectable effect on the time-average boundary-layer development. No turbulence intensity measurements were made.

Related references: Tomsho, 1978; Tomsho and Brown, 1978

FUTURE ADDITIONS TO THE DATA LIBRARY

Although every possible effort was made to ensure the completeness of this compilation of unsteady turbulent boundary-layer data, inevitably some experiments have been inadvertently overlooked. The compilation effort will continue, however, and contributions of experimental results, new or old, are welcomed. Data in computer-compatible digital form is particularly valuable, but any information forwarded to the author concerning unsteady turbulent boundary-layer experiments not reported in this paper will be appreciated.

Although there are new experiments in progress in the United States and in Europe, the publication schedule made it impossible to include detailed descriptions of many of them in this report. It is possible that the results of the experiments shown in Table 3 will be compiled at a later date.

COMMENT CONCERNING BIBLIOGRAPHY

The bibliography contains all the reports about unsteady turbulent boundary-layer experiments that have been identified.

A limited number of references are presented that involve unsteady laminar and transitional experiments. Although they are not directly related to the present subject, they can offer significant insights into unsteady viscous flow behavior and can be useful in evaluating the unsteady turbulent boundary-layer results, which are the main emphasis of the present work.

In addition, the literature review uncovered many reports whose titles imply possible relevance to unsteady turbulent boundary-layer experimentation, but whose contents are not appropriate to the present task. Even though these reports are not directly relevant, they are included in this bibliography (1) to indicate that they were reviewed, and (2) to reduce the ambiguity concerning them as much as possible.

It should be mentioned that there are unsteady flow references (mostly concerning theoretical and numerical techniques) that are not cited; the titles of these reports are quite unambiguous, and are obtainable by straightforward literature search techniques. Some of the listed reports are somewhat dated, but they have been included in the present list because it is not expected that a similar search on this subject will be necessary, and full documentation of the findings of the present study was considered appropriate.

The bibliography is presented alphabetically, with each report identified by a literature code to guide potential users. This code, which appears in parenthesis at the end of each citation, indicates the primary emphasis of the related report. The code is as follows:

Bibliography Literature Code

- G - Reports of general interest
- LE - Laminar experiment (unsteady)
- LT - Laminar theory (unsteady)
- NR - Not reviewed at time of publication; included for reference
- R - Review paper
- TE - Turbulent experiment (unsteady)
- TE-A - Detailed review herein, with digital data
- TE-B - Detailed review herein, without digital data
- TE-C - No instantaneous data, or insufficient data; citation only
- TE-D - Experimental techniques and other related topics; citation only
- TRE - Transition experiment (unsteady)
- TRT - Transition theory (unsteady)

CONCLUDING REMARKS AND RECOMMENDATIONS

Existing experiments on unsteady turbulent boundary layers have been reviewed and documented. These include flat-plate, diffuser, pipe, airfoil, and cascade flows. Based on that survey of experiments, a comprehensive bibliography was prepared and the various reports were classified to indicate the type of experiment that was performed.

The experiments that provide instantaneous boundary-layer measurements are described in detail using a standard format. A complete listing of the available data (graphic and digital) is presented for each experiment. Digital data, if available, are stored on digital tape. However, many of the experimental results no longer exist in digital form.

The available digital data will be supplied in the form of a computer tape upon request. The procedure for access to these data is described in the Appendix.

Additional unsteady data are needed to guide future theoretical developments. Based on the author's experiences in preparing the present report, the following recommendations are offered:

1. Any future experiment in which unsteady turbulent boundary-layer behavior is studied should document the results in digital form, using the format outlined in the present paper.
2. The initial condition of the boundary layer at upstream stations should be documented. This information may be as important as the results obtained at the nominal test position, even for "fully developed" flows. Unless information about the character of the flow at these earlier stations is recorded, the effects of unsteadiness are very difficult to separate from the effects of upstream history.

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APPENDIX

ACCESS TO DATA TAPES

Collecting digital data for unsteady, turbulent boundary-layer experiments has proved to be a complex and arduous task. Much of the data no longer exist in digital form; the data that do exist appear in a wide variety of formats; new experiments are in progress; and new results will continue to appear. As a result, the digital library associated with this report is by necessity not complete.

The experimental data that are available in digital form have been stored on magnetic tape using the IBM 360-67 computer at Ames Research Center. The digital data have either been supplied by the original experimenter or have been re-digitized by the present author. The data are presented in unaltered form; no smoothing or modification of any kind has been performed. In order to facilitate later additions and modifications of these tapes, details of the various data files will be presented only on the tapes themselves. Information in the present report will be restricted to specification of the tape parameters, and instructions for accessing the first file in the library. This first file will contain full instructions for processing the data sets, and each data set will be accompanied by a computer program for reading the requisite data.

These tapes will be available on a temporary loan basis from the Aeromechanics Laboratory, U.S. Army RTL (AVRADCOM), MS 215-1, Ames Research Center, Moffett Field, Calif. 94035. Upon receipt of a written request specifying the experiments required, the requested data tapes will be sent, along with an updated catalog of experiments. After transferral of the related data into the requestor's computer system, the original tapes are to be returned. A set of these tapes will also be made available to ONERA-CERT/DERAT for distribution in Europe.

DESCRIPTION OF DIGITAL DATA TAPES

File 1 is an introduction that contains details describing the data hierarchy and data access procedure. This file provides a catalog listing of the various available data sets on file, and a program that will permit access to each data set independently. This file is written in A format, and can be read with a minimum of programming effort.

There are 600 lines allocated to this introductory file, each 80 characters in length, formatted in 80A1. The following program is recommended for reading this file; the job control cards are written for operation on the Ames IBM 360-67 computer:

```
DDEF FT05F001, VS, LEADFILE
SOURCE.AGDRD$$
DIMENSION TEXT(80)
DO 5 J=1,600
  READ(5,10)(TEXT(I), I = 1,80)
  5 WRITE(6,11)(TEXT(I), I = 1,80)
10 FORMAT (80A1)
11 FORMAT (1X, 80A1)
STOP
END
```

Each experiment is presented as follows: first, a read/write program in 80A1; then a data file containing a description of the relevant digital data; and finally the digital data. In many cases, the data are stored in the form supplied by the originating author; the rest are tabulated based on 80-column storage.

SAMPLE TAPE ACCESS (AS PERFORMED ON THE AMES IBM 360-67)

```
MTMSG
*** 9-TR TAPE AGDSAM, WITHOUT RING ****
AMES UTIL
DDEF DDUTPSRD,PS,DUMMY,UNIT=(TA,9D3), LABEL=(1,NL),-
  VOLUME=(,AGDSAM),DISP=OLD,-
  DCB=(LRECL=80,BLKSIZE=6400,RECFM=FB)
DDEF DDUTVSWT,VS,LEADFILE,DCB=(RECFM=F,LRECL=80)
UTILTVS
UTILTVS1      654 RECORDS COPIED FROM FILE      1 (DUMMY) TO LEADFILE
RELEASE DDUTPSRD
RELEASE DDUTVSWT
DDEF DDUTPSRD,PS,DUMMY,UNIT=(TA,9D3),LABEL=(2,NL),-
  VOLUME=(,AGDSAM),DISP=OLD,-
  DCB=(LRECL=80,BLKSIZE=6400,RECFM=FB)
DDEF DDUTVSWT,VS,DATA.JONNISON,DCB=(RECFM=F,LRECL=80)
UTILTVS
UTILTVS1      366 RECORDS COPIED FROM FILE      2 (DUMMY) TO DATA.JONNISON
RELEASE DDUTPSRD
RELEASE DDUTVSWT
```


INTRODUCTORY FILE (AS WRITTEN ON TAPE)

File 1: Unsteady Turbulent Boundary Layer Digital Data From Selected Experiments - Data Catalog and Procedural Instructions Are Included

Date of Most Recent Modification: June 11, 1981

References:

(1): Carr, L. W.; "A Compilation of Existing Unsteady Turbulent Boundary Layer Experimental Data," AGARDograph 265, 1981

(2): Carr, L. W.; "A Review of Unsteady Turbulent Boundary Layer Experiments," IUTAM Symposium on Unsteady Turbulent Shear Flows," 5-8 May 1981, Toulouse, France

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Research and Technology Laboratories (AVRADCOM)
MS 215-1, Ames Research Center, NASA
Moffett Field, CA 94035

INTRODUCTION: This tape, and the ones that follow, contain digital data for experiments relating to unsteady turbulent boundary layer investigations. The digital data have either been supplied by the original experimenter, or has been re-digitized by the present author. The data are presented in their original form; no smoothing or modification of any kind has been performed. Since the data obtained by the various experimenters range over a wide variety of parameters, each experiment is presented using read and write programs specifically written for that experiment. These access programs form the initial file of each data sequence, and are written in 80A1 format. In the following catalog, there is no intended hierarchy in the sequence that has occurred during the storage of the data. New data sets will be added as they are supplied to the present author.

The data sets are filed using the senior author of the related report for identification; the user is referred to the AGARDograph for further details of the various experiments.

DATA TAPE CATALOG

[The remainder of this file is contained on the tape]

REPORT DOCUMENTATION PAGE

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